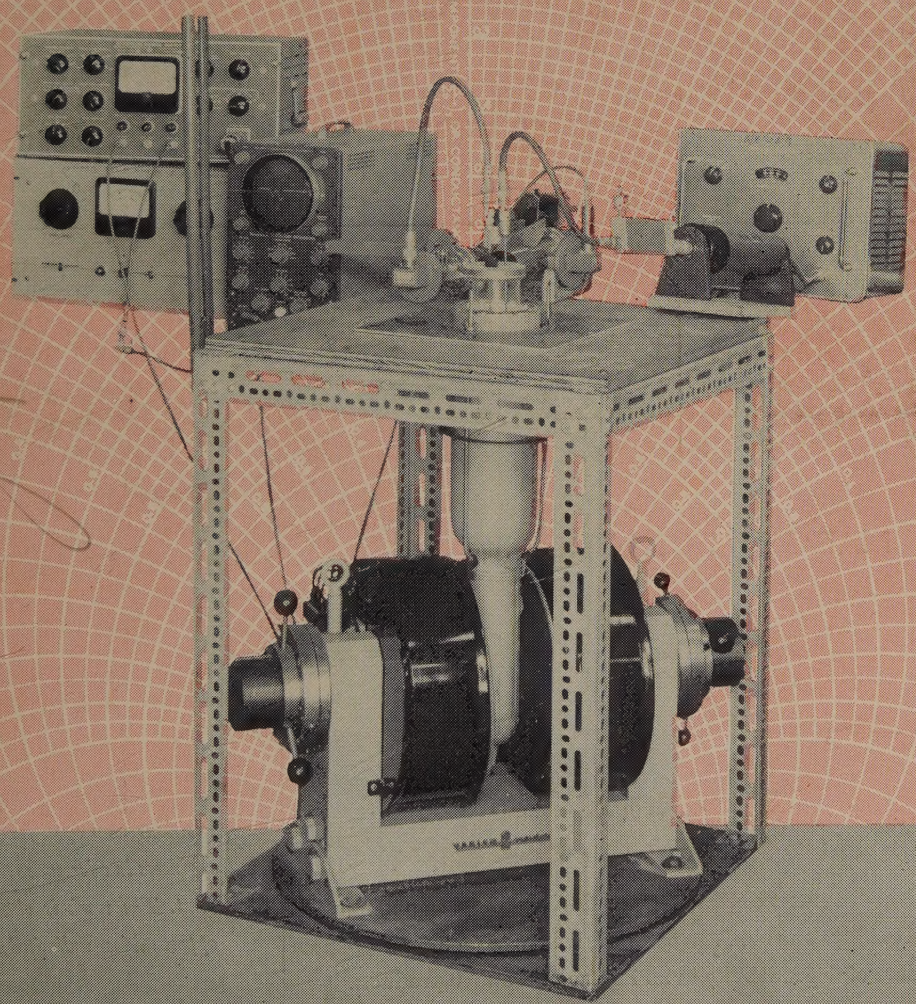
NOV.-DEC. '58
VOL. 1 • NO. 3

- From — The Maser
- Rizzi — Ferrite Rotators
- Ginzton — Microwaves II
- Bomac Company Profile
- R. C. Sanders — Biography

the microwave journal



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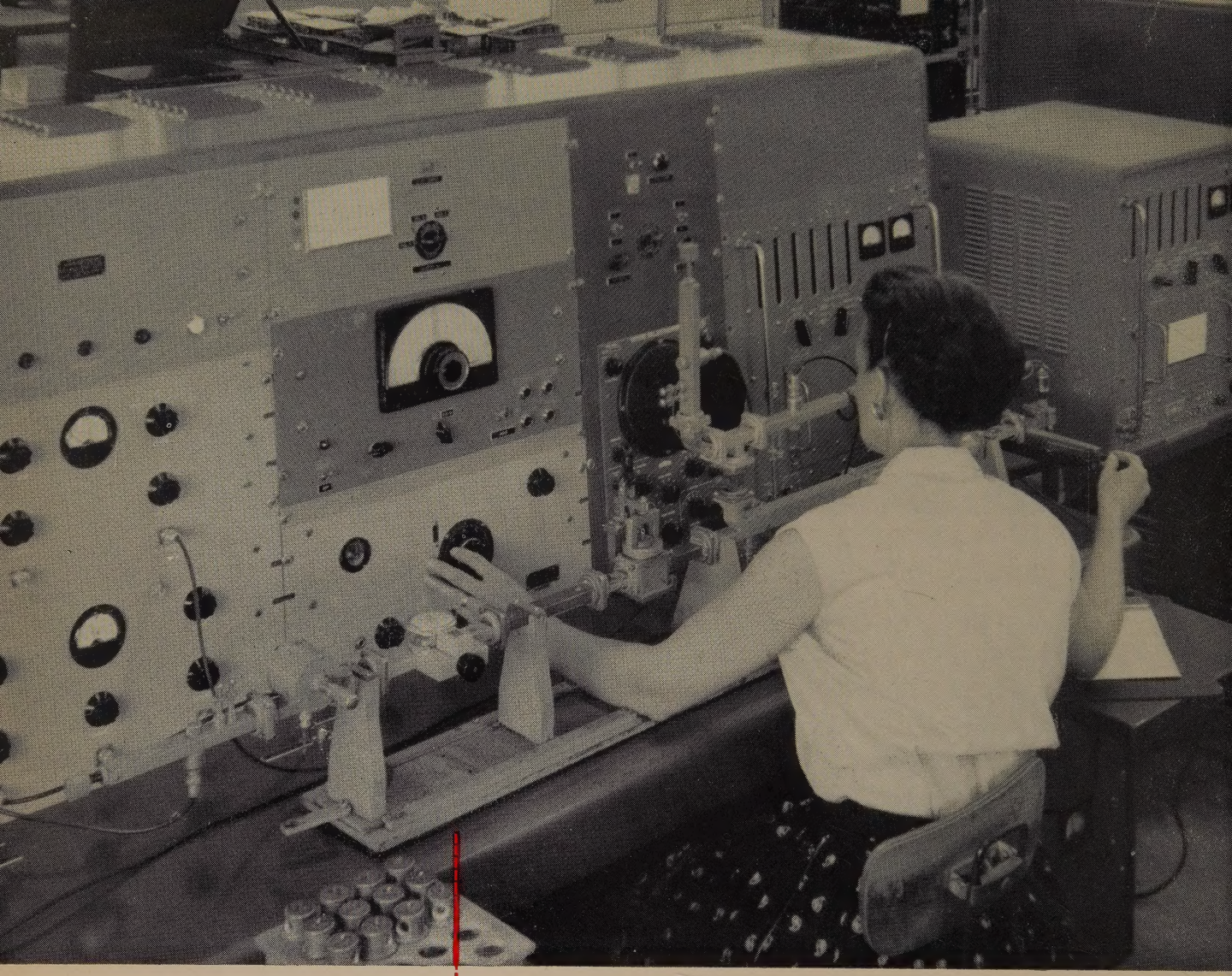

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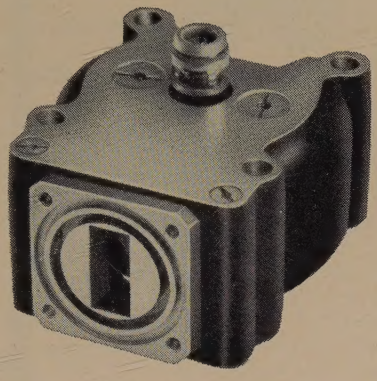

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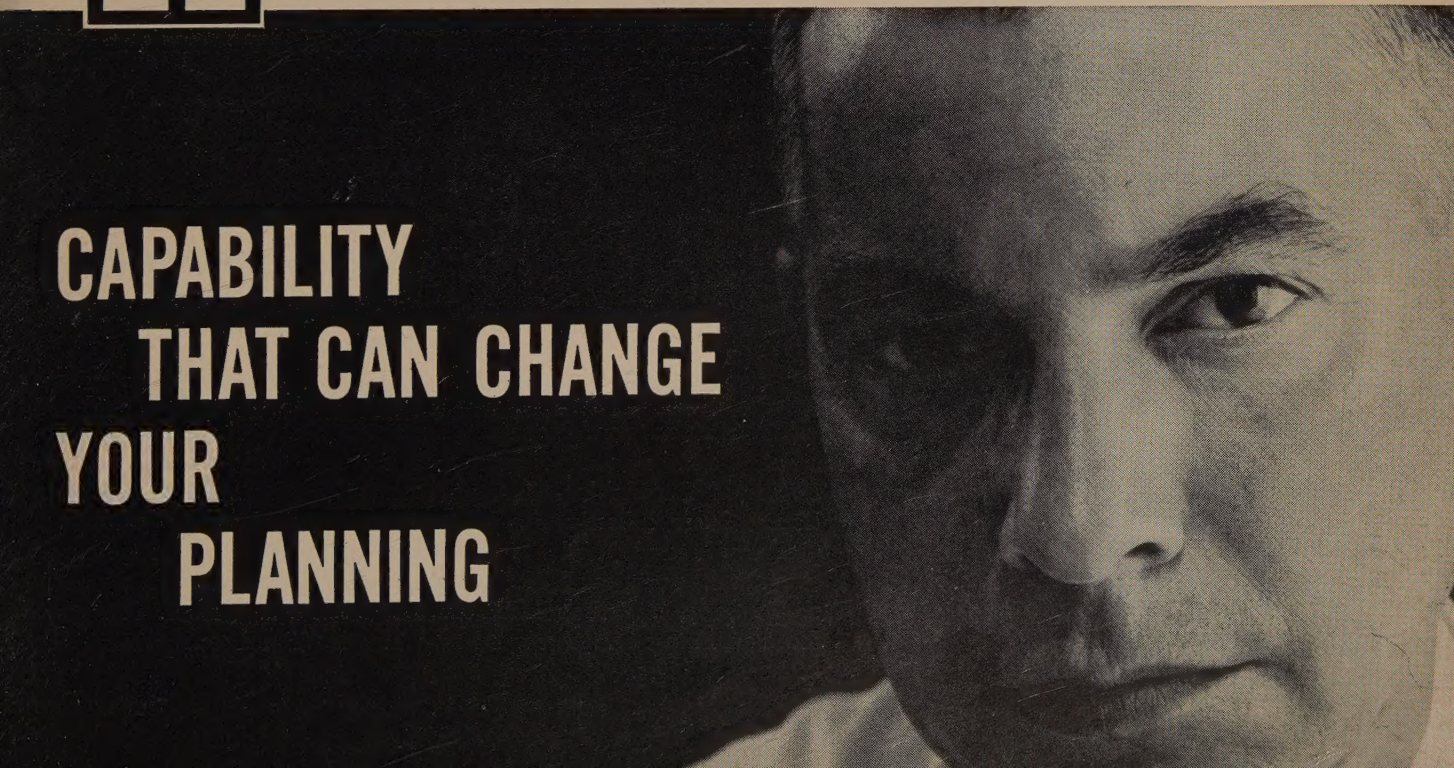

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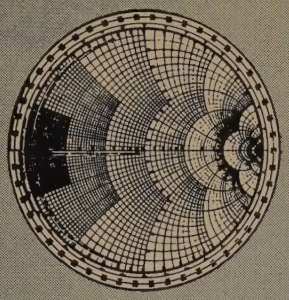

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COVER PICTURE

A typical laboratory facility described in "The Maser," Page 18, this issue.

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X	8.20-12.4	1 x ½	1030	175.
KU	12.4-18.0	.702 x .391	1029	180.
K	18.0-26.5	½ x ¼	1028	295.
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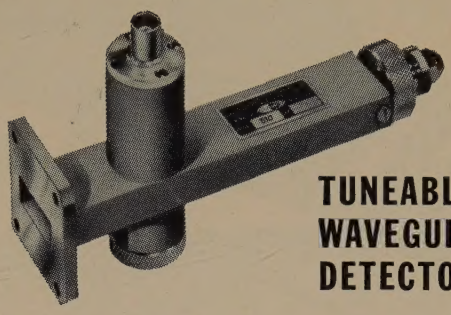

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XB	7.05-10.0	1¼ x ⅝	511	N610B	N821B	N605	N333D or N333	N334	1.25	IN23	85.
X	8.20-12.4	1 x ½	510	N610B	N821B	N605	N333D or N333	N334	1.25	IN23	75.
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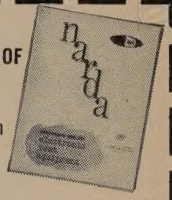

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†*Maser Action in Ruby*, by G. Makhov, C. Kikuchi, J. Lambe, and R. W. Terhune. "Physical Review," Vol. 109, No. 4, p. 1399, Feb. 15, 1958.

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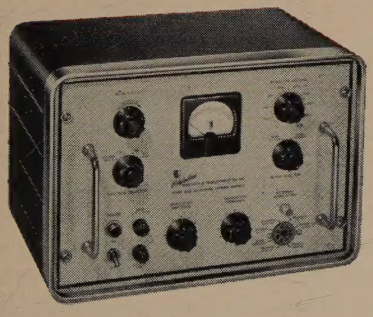

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OUTPUT		Type 812	Type 809
Beam	Volts, dc	200 to 3600	250 to 600
	Current, ma	0-125	0-65
	Ripple, mv rms	5 max.	5 max.
Reflector	Volts, dc	0 to —1000	0 to —900
	Current, μa	50 max.	50 max.
	Ripple, mv rms	1 max.	10 max.
Grid	Volts, positive	0 to 150	—
	negative	0 to 300	
	Current, ma positive grid	5 max.	
	Ripple, mv rms	3 max.	
MODULATION		**Type 812**	**Type 809**
Square Wave	Frequency, cps	500 to 5000	400 to 2000
	Volts*	0 to 150 (clamped)	0 to 90
Pulse	Frequency, cps	500 to 5000	—
	Volts*	0 to 150 (clamped)	
Sawtooth	Frequency, cps	40 to 120	60, fixed
	Volts*	0 to 200	0 to 125
Sine Wave	Frequency, cps	60, fixed	—
	Volts*	0 to 200	

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ANTENNAS . . . . . .

BY

Carlyle J. Sletten

AFCRC

THE ANTENNA STANDS strategically at the gateway to all later electronic processes of all radiating equipments. Later amplification, filtering, and correlating cannot increase the basic information captured by the antenna.

Their Function . . .

Classically the function of the antenna is selective summing of electromagnetic signals on the basis of polarization, phase and amplitude. This is a linear process resulting in directional properties or preferential gain in certain directions. Engineers now recognize the antenna as a first stage in their system capable of additional processes on guided vector waves. Amplifiers, sources and switches are now distributed around the antenna contour to effect complicated pattern scanning and signal comparison operations. The keynote in contemporary systems design is functional simplicity; the traditional electronic components are merging, and the dominant role of the antenna as a primary transducer of electromagnetic information becomes more evident.

To strange eyes from other worlds, the dishes, wires, and poles that shape our antennas might reasonably appear to be a new flourishing species of earth vegetation. Whether the shadowy giant reflectors of the Arctic or the tawdry television antennas of the cities, antennas intrude conspicuously upon the modern scene. It is hardly news to us in the electronics industry that antennas are a booming business. However, engineers feel a little uneasy when asked to identify and assess economic and technological forces that undergird the rapid growth of antenna art, or to forecast future trends.

Their History . . .

A few years ago antenna design was a mystic art, practiced by a few radio broadcasting engineers. Even more mysterious were the formulae and pronouncements of a few college professors explaining the nature of radiation. The second World War saw vast new regions of the spectrum—VHF, UHF, and microwaves being developed for an endless number of military functions. While it is true that certain nonmilitary needs in television and commercial industries have stimulated inventiveness in antennas, many of the first magnitude antenna improvements have come about through solutions of problems in radar, sonar, weapon guidance, countermeasures, etc. It has been the intense activity in quest of operational answers mainly in the fields of detection and control of modern weapons that has fostered rapid advances in antenna technology rather than important new theoretical advances.

Rigorous antenna theory appears to rest securely on a long established system of Maxwell's equations which presumably completely describe all possible antenna phenomena. This theory is so impregnable and self-contained that speculative physicists tend to tackle more inviting areas. Also, the solution of Maxwell's equations is intractable when applied to practical problems; therefore, the engineer usually resorts to optical and array techniques to fashion antennas for scanning, synthesis and operational objectives. The systems engineer rather than the theoretical physicist has been and probably will continue to be at the helm of the antenna and associated component evolution. Although the motive force for antenna research springs primarily from intriguing military games of seeking, concealing, jamming and guiding, this does not make the antenna engineer's horizon any less exciting.

Their Creators . . .

Because antennas are shaped to perform an ever growing number of functions, they occupy a very busy crossroad on our scientific highways. To the electrical engineer, antennas require just a minor extension of network and circuit principles. To the man whose

experience is in optics, the antenna stands for microwave lens and reflector designs. The mathematician sees antennas primarily in terms of statistics, information theory or perhaps analysis of special functions. Problems caused by the structural support in huge reflectors and the complexities of high speed scanning mechanisms have taxed the ingenuity of many mechanical engineers. The combined talents and insights of men from mathematics, engineering and physics have greatly enriched the fecundity in the antenna field.

Of these various scientific disciplines, all have been productive of creative ideas. Electromagnetic theory provides a solid conceptual framework for understanding the ultimate limitations of antenna capabilities. Electromagnetic engineering, although enjoying great success in solving problems in cavities and guiding structures, has been restricted mainly to a few relatively simple antenna configurations. There is some hope that physicists in close alliance with mathematicians can sum and tabulate certain key mathematical series which will permit engineering solutions of a number of "exterior" boundary value problems.

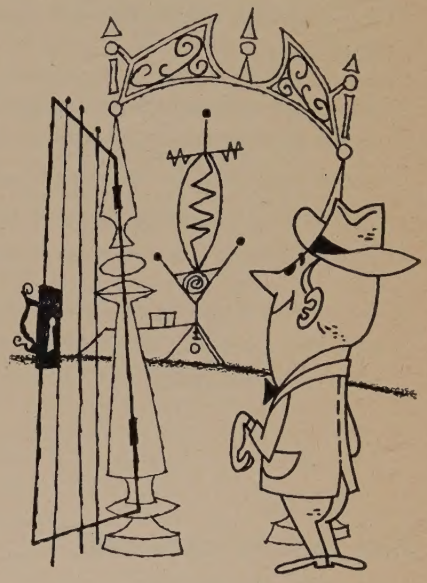
The antenna engineer bases his design strategy largely on a rapidly growing stockpile of microwave optics and array synthesis techniques. He will need help from specialists in information theory and systems engineering to precisely define and plan the functions to be performed. He will have to work closely with men in the fields of solid state physics, low noise receivers, and radiating sources in order to incorporate these new elements into a geometric region called the antenna.

Their Future . . .

Having looked briefly at the foundation of the flourishing antenna business, let us risk a quick glimpse into the future. Supposing for a moment that the predominant functional demands will be of military origin, we can foresee an "upward look" in antennas as air breathing sources become extinct and space vehicles fly at much higher elevations. For a long time to come earth-to-space communication and detection will require antennas using spectra in the "window" where neither ionospheric nor atmospheric effects prohibit operation. This need will spur the development of huge UHF antennas scanning most of the upward hemisphere about the zenith using low cost per unit area techniques. These antennas may take the form of simple mechanical motions of radiators flat on the ground or gigantic fixed reflectors scanned by motion of primary feeds. Freed from the restrictions imposed on radiation through the atmosphere, spacemen will no doubt use much of the entire spectrum in countless fascinating ways (too numerous to speculate on here). Certainly, there will continue (for some time) to be a severe penalty for added weight on space vehicles. Quasi-optical systems using very short wavelengths will minimize the size of antenna apertures. Every effort will be made to use the ever present solar energy directly or with high conversion efficiency for communication, detection and guidance systems. But in an environment which features high vacuum, low accelerations and weightlessness, antenna structures can be expected to assume some bizarre forms. The great need will be for back-to-earth control and communications which can be, perhaps, best accomplished at frequencies from 100 to 3000 Mcps.

Turning to more prosaic but equally difficult problems of coping with ever increasing problems of identifying, tracking and handling increasing numbers of signal inputs, antenna designers will make more use of multiport structures to increase information rates. The phase-in-space diagram of antennas will become as familiar as the power patterns. Electronic scanning will allow sophisticated search and pattern-shaping operations to be done in simple, natural ways. Information theory will teach us how to optimize our pattern and side lobe levels for every operation and antennas composed of disturbed, active and variable parameters will obey instantaneously the functional demands.

Techniques will doubtlessly be found to place giant radar and communication antennas nearer the ground. Vulnerability to wind and war damage as well as construction cost all conspire to make low silhouette antennas essential. Large radio interferometer antennas with extremely good unambiguous resolution seem to be possible very soon, due principally to the very able men working in radio astronomy.



Conclusions . . .

We could continue to conjecture at length about the new forms and uses of antennas for tomorrow. But this we *can* confidently expect,—antennas will continue to be of strategic importance in at least the three basic senses we have discussed: (1) Antennas stand strategically as a gateway to the electronic system of which it is a part; (2) Antennas are strategic in the true military sense because they are essential to modern military functions; and (3) Antenna development profits from the efforts of a rich confluence of scientists and engineers drawn from various disciplines and backgrounds.

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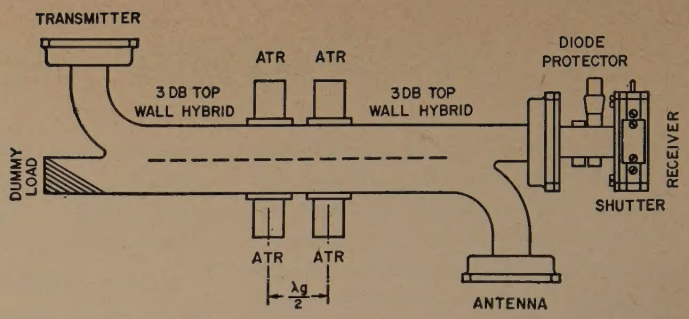

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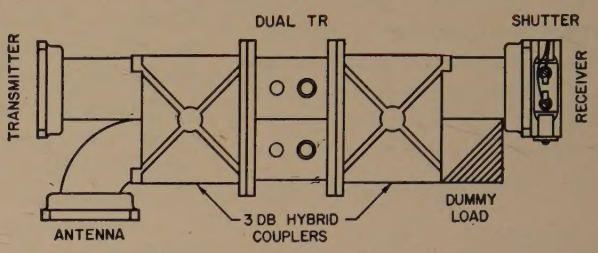

BALANCED DUPLEXER: DUAL TR, SHUTTER

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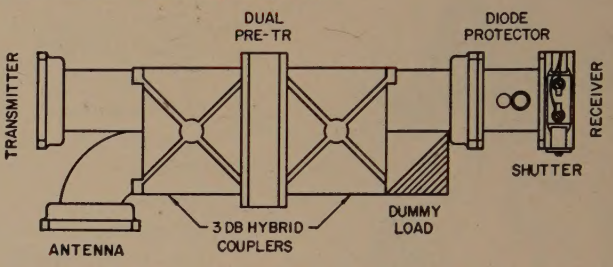

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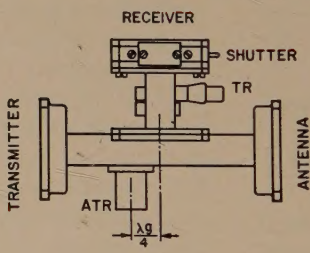

BRANCHED DUPLEXER: ATR, TR, SHUTTER

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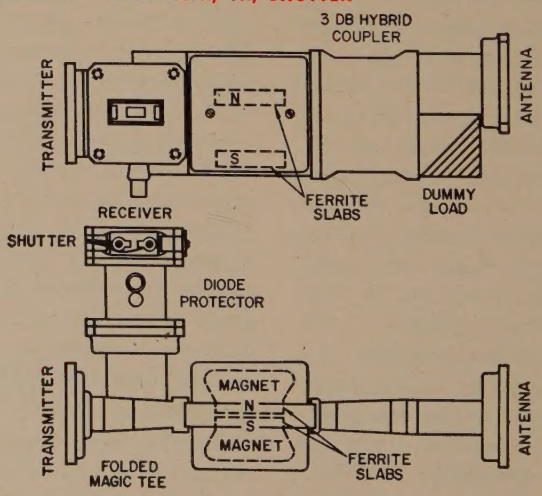

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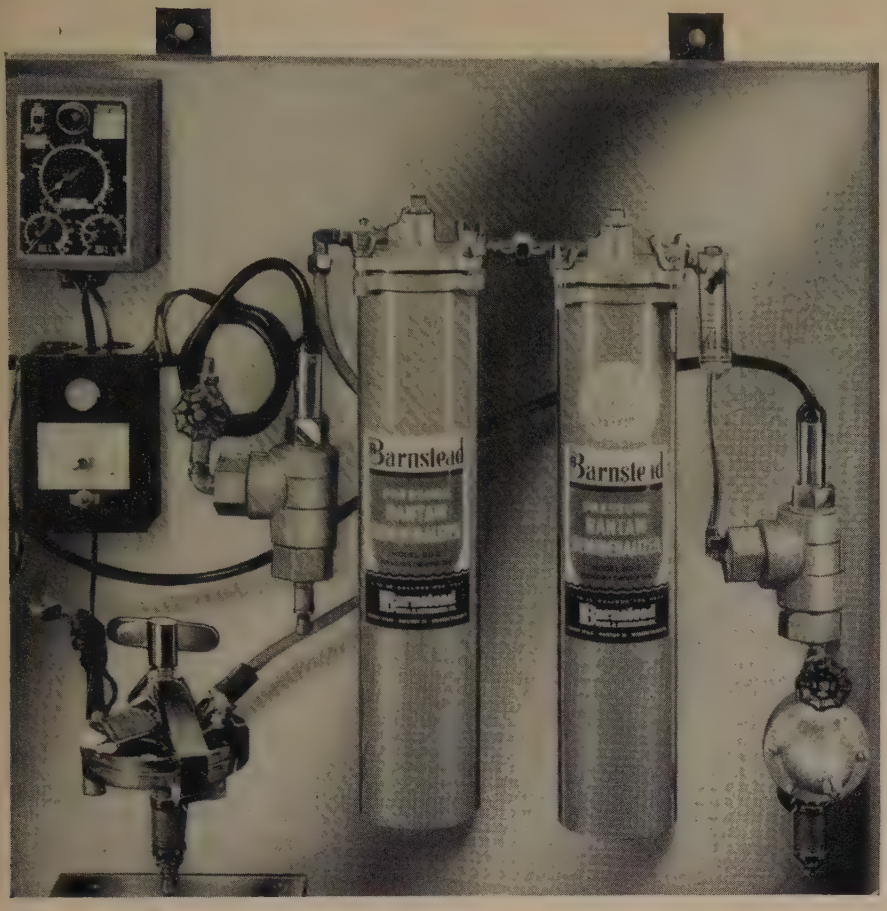

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Research by a leading transmitting tube manufacturer shows that the life of UHF transmitting tubes is drastically shortened by impurities in cooling water. Dissolved impurities and suspended particles in the cooling water deposit on the tube anode forming an insulation. This causes overheating, and shortened tube life results. The most damaging of these impurities is copper oxide which is formed when carbon dioxide dissolves copper particles in the cooling water. The Barnstead Cooling Water Repurifying System substantially reduces and sometimes completely eliminates the copper oxide deposits by removing the dissolved copper, carbon dioxide and oxygen. Other dissolved scale-forming impurities are removed at the same time including submicroscopic particles. For the answer to your Pure Water Problems why not write to Barnstead today!

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CIRCLE READER SERVICE CARD 6

Persons . . . . . Places

SYLVANIA NAMES MEYER LEIFER AS MANAGER OF SPECIAL TUBE OPERATIONS

Meyer Leifer, whose appointment as manager of Special Tube Operations for Sylvania Electric Products Inc., has held managerial posts for Sylvania on the West Coast for the past five years.

In his new post, with headquarters at the company's Mountain View location, he will be responsible for directing an "expanding program of research, development and production in the microwave field," including special tube and component work.

Included in his organization will be production facilities at Mountain View and Williamsport, Pa., and the Microwave Tube and Microwave Physics Laboratories which have been grouped into the Microwave Components Laboratories in Mountain View.

Previous to his new appointment, Mr. Leifer had been manager of the Microwave Tube Laboratory in Mountain View. He joined Sylvania in 1946 as an engineer in Sylvania's Physics Laboratory in Bayside, N.Y., becoming manager of the systems and circuits branch in 1951.

Move Will Consolidate Sylvania's Microwave Operations

The move of Special Tube Operations headquarters to the West Coast, Mr. Leifer said, was made to "consolidate the microwave operations" of the company in order to "expand development and production of the wide range of special tubes and electronic components now being carried on."

Royden C. Sanders

President, Sanders Associates

Royden C. Sanders, Jr., President, Sanders Associates

ROYDEN C. SANDERS, JR., better known as Sandy, has always exhibited a talent for knowing what he wants to do and a will to do it. As a Junior at *Rensselaer Polytechnic Institute,* Sandy requested permission of his instructors to work on his basically new concept of a FM radio altimeter as a part of his school work. He was denied this on the ground that his project was too complicated for an undergraduate. Sandy, completely in character, replied that if he couldn't work on it at school he would do so in his own backyard in *Audubon, New Jersey.* This he did. He has been grabbing the proverbial bull by the horns ever since.

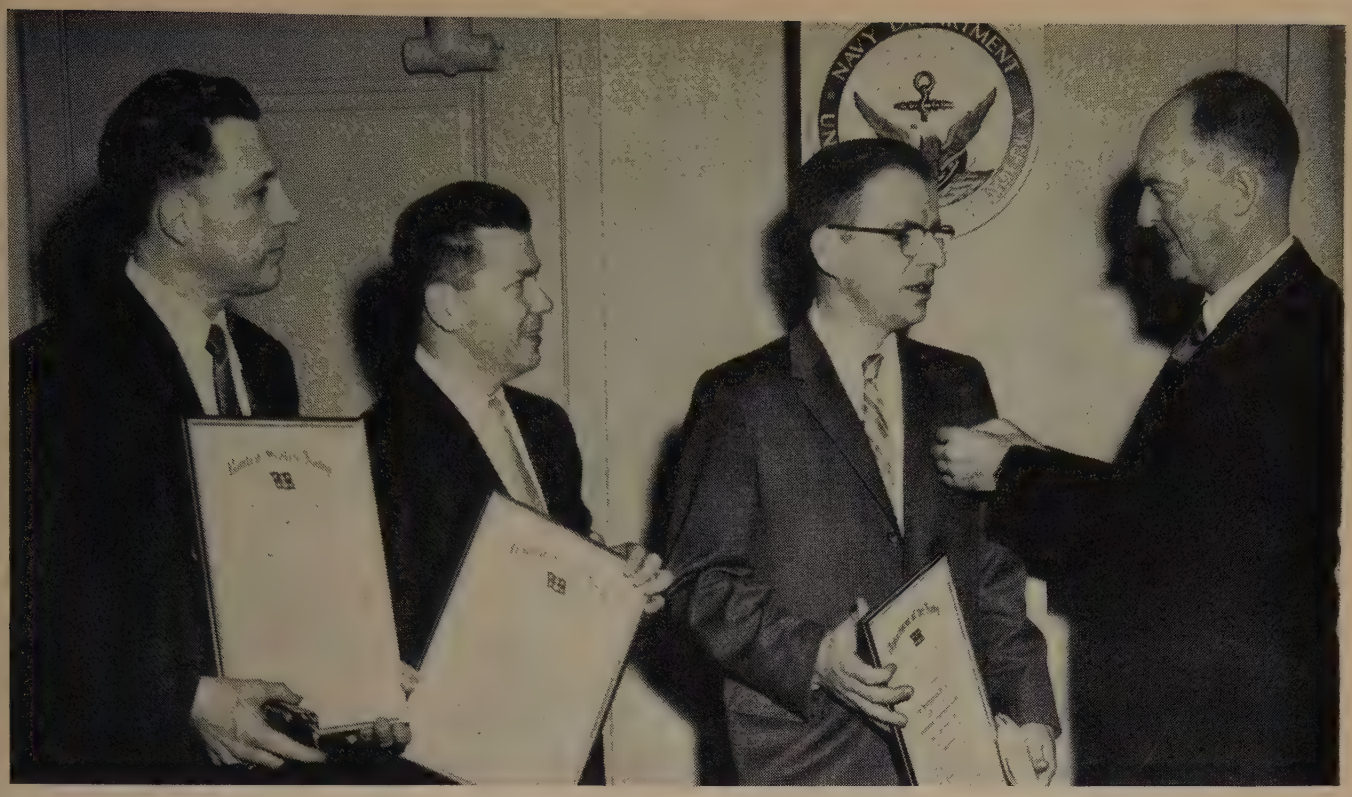
Royden Sanders is a complex person — on the personal or truly human side, he is deeply interested in the welfare of people, sometimes to the point of becoming deeply involved — on the intelligent machine side he is a combination of a keen, highly analytical mind, an unusual imagination for finding amazingly simple solutions, and bulldog tenacity in seeing a task once undertaken successfully completed. His actions after school disapproval of his project are exemplary of the latter characteristics.

First he wrote an elaborate and highly technical article on the project and submitted it to the Institute of Radio Engineers. For some reason it was not published. In his backyard he proceeded to assemble readily available, but crude, materials to put his concept into tangible form. He progressed sufficiently well to satisfy himself that he could construct a workable model. Because of lack of funds he hitch-hiked to the Wright Air Development Center and proposed his novel concept. The Air Force, though they liked the idea, were reluctant to trust such a highly technical project to one so young.

All of these seeming failures in no way diminished his determination. He continued his efforts in his backyard, further convincing himself of the soundness of his concept. Dr. Irving Wolfe, then associated with RCA, suggested that Sandy submit his concept to RCA. Sandy was reluctant to sacrifice his independence and joined *RCA* only when it appeared that a Bell Telephone development might provide an altimeter before he could with his limited funds. His faith in his concept and his determination were rewarded when the Bell Telephone project fell far short of satisfactory performance, while his AYB Program at RCA achieved success beyond the expectation of anyone but Sandy. This was the first of many altimeters developed under Sandy's guidance, resulting finally in the well-known AN/APN-1 used by the U.S. Navy and Air Force and the British forces.

Though thoroughly tenacious once a project is adopted, he is completely flexible in selecting a project. He undoubtedly is best known for his work in altimeters. However, he has successfully headed programs on missiles, radar and other navigational devices. At Raytheon, after leaving RCA, he was Manager of the Radar and Missile Division — better known at that time as Lab 16. While manager he initiated the development and produced the first successful tactical anti-aircraft missile, namely, the Lark. He followed this up with starting the development of the Hawk and Sparrow III Missiles, now being manufactured by Raytheon. For this work he was rewarded in 1958 by the Navy's Distinguished Service Award — the most distinguished award for civilians.

Excerpts of the statement by the Hon. Garrison Norton, Assistant Secretary of the Navy for Air read:



Left to right: Wm. Ralph Mercer, Director of Research, Sanders Associates; Martin R. Richmond, Executive Vice-President, Sanders Associates; Hon. Garrison Norton, Assistant Secretary of the Navy for Air making the presentation to Royden C. Sanders, Jr. in the Pentagon, February 26, 1958.

Gentlemen, it is my pleasure and my privilege to present awards to you today in behalf of the Secretary of the Navy for your significant contributions to the national defense.

Security considerations prevent my disclosing, except in general terms, the technical details and applications of equipments evolved largely from your pioneering efforts. However, it will become evident that the original missile guidance work performed by you, as leaders of a team at the Raytheon Manufacturing Company, has led to a number of successful applications which materially benefit the Navy's and the Nation's defense. . . .

Notwithstanding his happiness with his programs at Raytheon, Sandy's yearning for independence never really left him. It finally exhibited itself in the assembling of ten other highly skilled engineers with himself to form the company which now carries his name — Sanders Associates, Inc. After much planning and discussion as to the nature of the company to be formed, and with much scraping to acquire the meager capitalization of $75,000, Sanders Associates, Inc. was formed in 1951. It was to be an engineering company having all of the attributes which engineers found lacking in other companies. To a large degree, even though Sanders Associates is now a medium-size company of over 800 employees, this wish has been fulfilled. In many ways Sanders Associates, Inc. is the alter-ego of Royden C. Sanders, Jr. His incisive mind and excellent imagination has helped him transform his activities from a state of heavy engineering with light administration to a successful president still involved with engineering. He has taken the company from initial assets of $75,000 to present assets of more than $3,500,000, from initial sales of $500,000 during the first year to sales of approximately $9 million at the end of the seventh year. The initial employment of 88 in the first year has now expanded to over 800.

Though Sandy has had to give up a great deal of his engineering to successfully further the interests of Sanders Associates, Inc., he has not lost his engineering ingenuity or acumen. The company under his direction was one of the first to demonstrate the many advantages of module construction. It has pioneered in printed circuit techniques providing ingenious printed circuit packages and the unique flexible printed circuit wiring, now receiving widespread acceptance. Sandy has not narrowed his scope of engineering accomplishments. The company is also well known as the pioneer in providing a sub-miniature rate gyro weighing approximately 3 ounces and in providing a wide range of electrohydraulic servo valves. Though the above would seem to be enough, Sandy has by no means lost his first love for microwave systems. Because of this, the company is also well known in the military systems field for its multiple target track and detection system, its APN-77 doppler navigator and for classified work on coherent pulse-doppler techniques for use in missiles. To round out the wide scope of activities directed by Sandy, the company is also well known for its strip transmission line, which is used in many of its systems as well as widely used by others in the field.

Sandy is still a relatively young man and his drive and ambitions have little diminished. If past results can be any indicator, his company should not only prosper but also continue to gain recognition for outstanding achievements in its field, for if Sandy has one attribute that is outstanding it is his dissatisfaction with mediocrity.

TOP LEVEL ENGINEER TO HELP DIRECT KEY RESEARCH PROGRAM IN MICROWAVE FIELD

Microwave Associates is expanding its progressive development program in the area of microwave energy control through gas discharges.

We seek an engineer or physicist who is well-founded in microwave theory and techniques and in gas discharge phenomena to direct a development group involved in the design of new duplexer circuits and tubes for advanced applications.

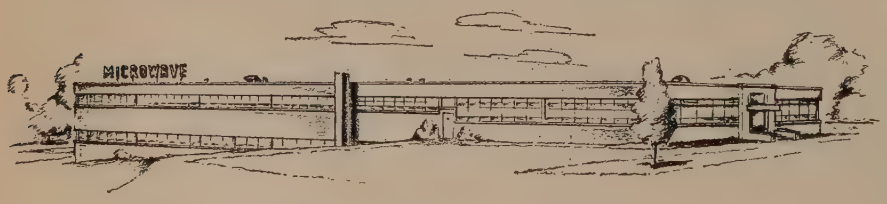
Excellent high power and low power facilities are available for complete study and test of these new devices and there is good opportunity for expansion into devices using ferrites and semiconductors.

Opportunities for your continued growth are excellent — Microwave Associates has enjoyed exceptional progress over the past several years and occupies a well established, recognized position in the field.

You are invited to a confidential exploratory discussion of your future with us. Contact Dr. Jerome Kornreich for suitable arrangements.

MICROWAVE ASSOCIATES, INC.

BURLINGTON, MASSACHUSETTS • Telephone: BRowning 2-3000



CIRCLE READER SERVICE CARD 7

Letters to the Editor

Gentlemen:

We are in receipt of your second publication of "the microwave journal" and wish to offer our congratulations on the technical excellence of the magazine. We were particularly impressed with "Microwaves, Part 1" by Mr. E. L. Ginzton. Since Frequency Standards was incorporated in 1948, no publication has come closer to being the ideal than "the microwave journal."

We would like to offer our services in any capacity that would further the success of "the microwave journal."

Yours very truly,
J. KELSEY BURR, III
Vice President of Marketing
Frequency Standards, Inc.

•

Gentlemen:

Having read the second issue of your magazine, I am convinced that the other engineers in the Microwave group here at Armour Research Foundation would be very pleased to be placed on your mailing list.

In my own estimation the microwave field has long had a need for such a magazine. The promise of future tutorial papers is highly anticipated, both for my own edification and for use in indoctrinating young engineers to this field. Too many times the other technical papers involve complexities which frighten away the novice.

Wishing you, for selfish reasons as well as for your own interests, success in this new endeavor.

Yours truly,
R. E. SAXE
Assistant Supervisor
Microwaves, Antennas and Propagation Section

•

Dear Sir:

A couple of months ago I received a copy of "the microwave journal" Volume I, No. 1. This magazine interested me very highly. Since I work with microwaves both at my job at Convair-Pomona, and as a hobby. I wish to keep abreast of all the latest developments.

In this area we have what we believe to be the only organization for the furtherance of microwave techniques from a radio amateurs standpoint. This non-profit corporation

"The San Bernardino Microwave Society" has done much work in microwave communication and propagation research.

The Society is very interested in the magazine and if desired would be most happy to provide a short article about our organization and its work.

Sincerely,
A. D. BREDON
Sr. Electronic Engineer

P.S. Just received Vol. I, No. 2; thanks and keep up the good work.

•

. . . May I commend you on your journal and cast my vote for survey and tutorial papers on tubes and antennas.

PAUL C. YUEN
Research Engineer
Ill. Institute of Technology

•

. . . I note in the September/October 1958 issue that the next issue is going to cover MASERS, a subject in which I am greatly interested. It would be greatly appreciated if you could arrange to start mailing with this issue.

MR. CHARLES L. BAXTER
Product Manager—Tubes
ITT
International Telephone and
Telegraph Corporation

•

. . . Having read the first two issues of your magazine, I would consider it a privilege to have my name placed on your mailing list for future numbers, if I am so qualified.

The balance, in the first two issues, between general technical articles and news of the industry and its personnel could not have been more welcome. Please continue your present editorial policy.

D. B. CLEMSON
Microwave Design
Engineering
Westinghouse Electric Corp.

•

. . . A copy of "the microwave journal" has recently come to my attention. It seems to be such a fine publication covering material in which we have great interest. I would like to receive the magazine regularly to circulate among our Research, Engineering and Purchasing Departments.

MRS. IVAH DEAN
Librarian
Stromberg-Carlson Company
Rochester, New York

EDITORIAL

In the past few years there has been a flood of new magazines, devoted either to the entire electronic industry, or some specialized branch thereof. The founders of "the microwave journal" felt that there was a decided need for such a magazine in the field of microwaves.

The original concept of the "journal" was that it should provide a forum for the entire microwave industry. This meant that the magazine in effect belonged to the whole industry and not to a selected few. The Editorial Staff has adopted the policy that the "journal" is held in trust for all qualified participants. All technical material, regardless of Company of origin, will be judged strictly on merit of content alone.

In time, "the microwave journal" will attempt to acquaint the engineer with all phases of the microwave field.

The main efforts will be devoted to the technical areas. It has always been our opinion that many excellent technical articles on microwaves were not receiving proper distribution.

The highly theoretical papers, which delve into higher mathematics, have always had several publication outlets. Papers dealing in basic or revolutionary engineering steps have also found a natural outlet. The purely engineering papers of a tutorial, survey, device distribution or measuring techniques, on the other hand, have had to be scattered throughout many different publications. In many cases, they were not published because they lacked general reader interest.

The "journal" is dedicated to the solution of this problem in the field of microwaves. By devoting ourselves exclusively to this field, we hope to furnish interested people with a single, main source of information of a useful engineering nature.

Coupled with the purely technical aspects of microwaves are the factors that many of us tend to belittle. Microwaves is a dynamic industry, made up of many fascinating industries and companies. The stories of these people and organizations should be of interest to all. To ignore these human factors is, in our opinion, to take the narrow view.

The business aspects of the industry will receive our very interested attention. The recent wave of mergers is of very special interest ("General Telephone and Sylvania, Litton et al, Etc.). In addition to the much publicized financial movements, we are equally interested in the effect this will have on the field in general.

To bring a purely objective point of view on business conditions in the microwave industry to the reader, we have been fortunate in having a Wall Street contact. In the near future, we hope to have an editorial on "How Wall Street Views The Microwave Industry."

The contents of the "journal" will be controlled primarily by two factors: first, by the material made available, and secondly, by the evidence of interest on the part of the reader.

In our next issue, we will feature the first part of a two-part paper entitled, "The Smith diagram." This is by Dr. George C. Southworth. There will be an interesting editorial by Dr. Benjamin Lax on, "Microwaves and the Solid State." In addition, there will be a paper on, "Microwave Education." This is by Dr. Susskind. There will also be a survey paper by Wesley G. Matthei on, "Recent Advances in Solid State Receivers." The biography will feature Dr. Ernst Weber of Brooklyn Polytechnic Institute. The Company profile will concern Microwave Associates.

We would like to encourage your participation in all areas of the magazine. All technical material will receive a prompt and comprehensive review. Your letters of comment will be read avidly. Your criticism is most welcome.

MICROWAVE AND SPECIAL TUBE NEWS from SYLVANIA

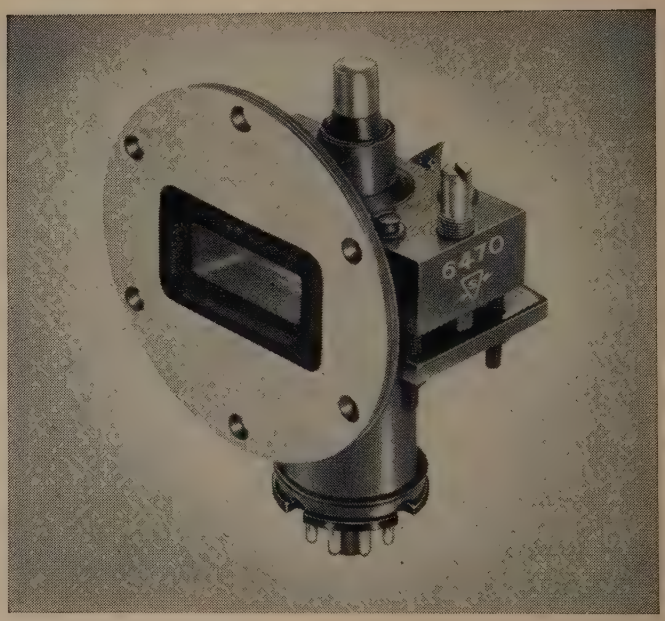
Sylvania Klystrons offer better performance at lower cost per year

Rigid quality control extends average service life of Sylvania Microwave Relay Klystrons by thousands of hours

A random sample of 10 tubes selected from recent production have provided a total life of over 45,000 hours, more than 4,500 hours for each tube, without a single failure. This outstanding result demonstrates why cost-conscious users select Sylvania Microwave Relay Klystrons for economy.

In performance too, Sylvania Klystrons are setting the pace by maintaining exceptional frequency stability throughout life. This superiority in both performance and economy results from Sylvania's experienced know-how in rigidly controlling electron tube quality.

The Sylvania Klystron line covers over 20 different types from Disc Seal types to the C-Band metal types listed. Many other klystrons specially designed for specific equipments are also available. Contact your Sylvania representative or write direct for full information on the Sylvania Klystron line.



Sylvania Microwave Relay Klystrons

Characteristics	TYPE K-841B	TYPE K-840B	TYPE K-839B
Mechanical Tuning Range – MC	6125 – 6425	6575 – 6875	7125 – 7425
Resonator Voltage – Volts	750	750	750
Reflector Voltage – Volts	-250 to -400	-250 to -400	-250 to -400
Cathode Current – MA	80 (max)	80 (max)	80 (max)
Power Output – Watts	0.7 (min)	0.7 (min)	0.7 (min)
Heater Voltage – Volts	6.3	6.3	6.3
Heater Current – Amperes	0.8	0.8	0.8
Flange Mates with –	UG 343 A/U	UG 343 A/U	UG 343 A/U

Fully specified parameters simplify equipment designs

Every Sylvania Klystron approved for shipment is *fully specified*. Beyond the information contained in ordinary data sheets, Sylvania offers full information on important characteristics such as:

- **Effective Resonator Position**
- **Beam Voltage Sensitivity**
- **Internal Noise Modulation**
- **Distortion**
- **Reflector Capacitance**

Availability of complete and exact data on every important klystron characteristic helps cut the guesswork out of design for the microwave engineer. Equipment specifications can be met accurately, confidently, and design adjustments can be avoided. Get complete information when you order Klystrons—specify Sylvania.

SYLVANIA

SYLVANIA ELECTRIC PRODUCTS INC.
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A report to engineers and scientists from Lockheed Missile Systems—where expanding missile programs insure more promising careers.

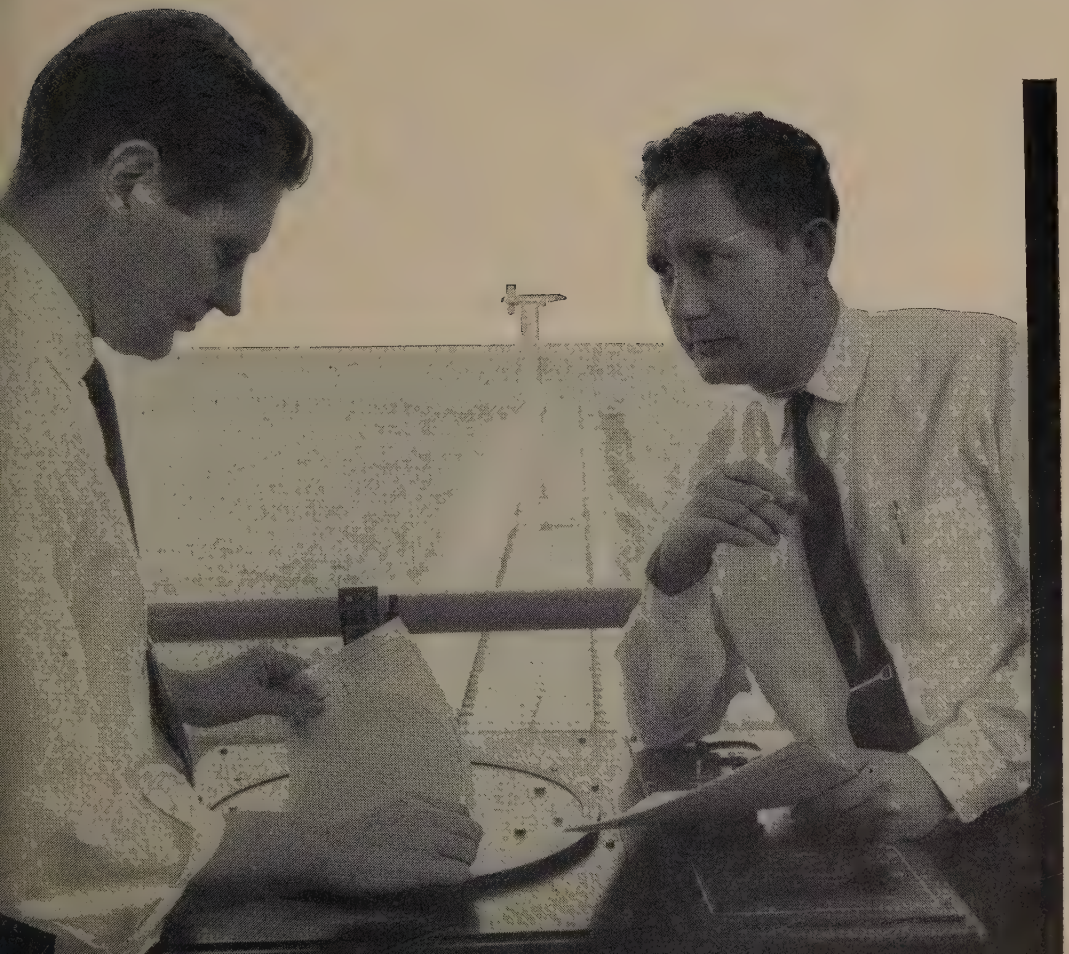
NEW LAB MEASURES ANTENNA PATTERNS; PROBES OUTER SPACE

A new laboratory at Sunnyvale, California today gives Lockheed scientists antenna patterns, scattering and propagation data, and promises exciting new discoveries in the problems of space communication. Laboratory studies include the effect of upper space on radar and radio signals, the radar pattern presented by space vehicles and missile shapes, and the design of antennas to survive the rigorous environment of the upper atmosphere and hypersonic speeds. Findings could pave the way for communication with manned space ships of the future or for the remote guidance of unmanned space ships.

Research and development studies by Division scientists contribute heavily to the projects that place Lockheed in the forefront of U.S. missile developers. These projects include the Polaris ballistic missile, Earth Satellite, Q-5 target ramjet, and X-7 test vehicle. Positions created by expansion on these and still other programs we cannot discuss offer unusual opportunities for advancement with our growing young division. Besides Antenna and Propagation, openings are in **Solid State Electronics, Telecommunications, Instrumentation, Radar and Data Link.** Other openings include **Information Processing, Reliability-Producibility, Ground Support, Flight Controls.** Please write Research and Development Staff, Dept 2711, Sunnyvale, California. For the convenience of those living in the East and Midwest, offices are maintained at Suite 745, 405 Lexington Avenue, New York 17 and Suite 300, 840 N. Michigan Avenue, Chicago 11.

Lockheed / MISSILE SYSTEMS DIVISION

SUNNYVALE, PALO ALTO, VAN NUYS, SANTA CRUZ, VANDENBERG AFB, CALIFORNIA
CAPE CANAVERAL, FLORIDA • ALAMOGORDO, NEW MEXICO



Mr. Emmanuel A. Blasi, right, Manager of Antenna and Propagation Department, discusses results of radiation performance after antenna pattern measurements with staff scientist Allen S. Dunbar. Column bearing missile in background is operated automatically from laboratory.

CIRCLE READER SERVICE CARD 9

R masers
parametrics
paramagnetic and
ferromagnetic materials

& **D** radio sextants
radio telescope receivers
microwave receiver-exciters
low noise microwave amplifiers

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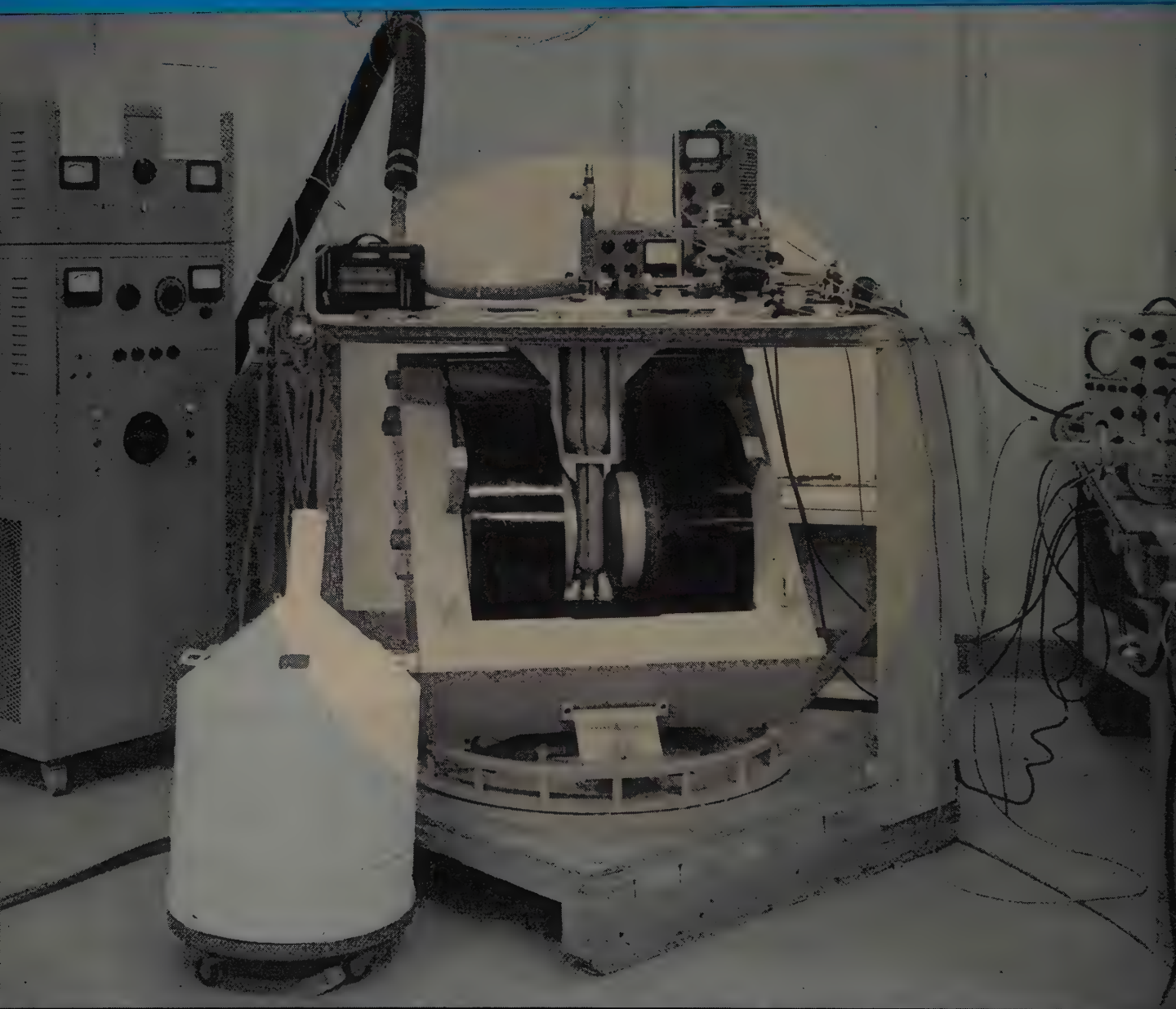
PREPARED TO MEET YOUR R & D REQUIREMENTS



Ewen Knight CORPORATION

AT THE FRONTIERS OF Electronics

NEEDHAM 94, MASS.

WILLIAM H. FROM

William H. From was born in Norfolk, Virginia on March 2, 1923. After serving as a Naval aviator during World War II, he returned to college and received his B.A. in Mathematics from the University of Virginia. While doing graduate work there he instructed undergraduate courses in Mathematics. Mr. From received his Master's degree from Northeastern University and since 1954 he has been taking advanced courses in Physics at Boston, Brandeis, and Tufts Universities.

Mr. From has worked since 1950 in the fields of microwave antennas and components, operations research, low noise front ends, and ferrites, and presently he is directing the paramagnetic and parametric amplifier research and development efforts at the Ewen-Knight Corporation.

Before coming to Ewen-Knight Mr. From was a group leader in charge of microwave systems development for such radars as Hawk, CAA, and Hustler, and also for commercial microwave link systems.

At Ewen-Knight he has directed their solid state group to first in the industry in the development of Masers. More recently his group has become interested in parametric amplifiers and they have built such devices in the low frequency region for the purposes of system evaluation. Other fields that they will explore are the non-linear properties of ferrites and their evaluation and application. These efforts are being directed for application in low noise receiver systems.

PETER A. RIZZI

Peter A. Rizzi was born in Providence, Rhode Island on December 10, 1930. He received the B.S. degree with high honors from the University of Rhode Island in 1951, and the M.Eng. and D.Eng. degrees in electrical engineering from Yale University in 1952 and 1955. His graduate work included a theoretical and experimental investigation of the electromagnetic field in composite ferrite and dielectric structures. During his graduate studies, he received the Yale University Scholarship and the Charles Le Geyt Fortescue Fellowship.

In August, 1954, Dr. Rizzi joined the microwave branch in the Missile Systems Division of the Raytheon Manufacturing Company where he was engaged in the development of high power ferrite devices, high frequency ferrite modulators and various types of microwave filters and frequency diplexers. As head of the microwave ferrite section he directed the development of ferrite phase shifters, isolators, circulators, modulators, single sideband generators and many other devices. In September, 1958, he joined the Ewen-Knight Corporation where he is presently engaged in the development of both linear and non-linear ferrite devices and various types of parametric amplifiers and converters.

Dr. Rizzi is a member of Phi Kappa Phi, Sigma Xi, Tau Beta Pi and the Institute of Radio Engineers.

CARLYLE J. SLETTEN

Carlyle J. Sletten was born in Chetek, Wisconsin on January 13, 1922. He received the Bachelor of Science degree with honors in physics from the University of Wisconsin in 1947, and a Master's degree in applied physics from Harvard University in 1949.

Mr. Sletten served for more than three years in the Air Corps during World War II as a Meteorologist and Radar Weather Officer. He has been with the Electromagnetic Radiation Laboratory of the Air Force Cambridge Research Center since 1948. During that time he has published several papers on antennas and electromagnetic scattering. His paper "A New Technique for Obtaining Tricoordinate Radar Information" was awarded first prize at the ARDC Science Symposium held at Massachusetts Institute of Technology in 1956. He has also contributed a new antenna pattern synthesis technique from which he derived "amplitude scanning." Mr. Sletten has obtained one basic patent and has four pending.

Mr. Sletten was appointed Chief of the Ground Antenna Section in 1954 and is presently Acting Chief of the Electromagnetic Radiation Laboratory.

Mr. Sletten is a member of Phi Beta Kappa, Institute of Radio Engineers, the American Optical Society, and the Scientific Society of America.

A new word has been introduced recently into the electronics vocabulary. This word, Maser, and its associated field of solid state physics portend new and exciting adventures for the microwave engineer and technician. The word was coined by Townes and his co-workers at Columbia University, and the letters it comprises stand for Microwave Amplification by Stimulated Emission of Radiation. The main purpose of this paper is to clarify the significance of these seven words which describe the amplifier rather succinctly by:

I Giving a short chronological sketch of the events which preceded the development of the device.

II Describing the design and other practical aspects of the device.

III Introducing some of the more important theoretical aspects governing the choice of materials.

IV Discussing the future of the Maser

THE MASER*

WILLIAM FROM
EWEN KNIGHT CORP., NEEDHAM, MASS.

I HISTORY

In 1945 Zavoiski, a Russian, discovered that a free electron exhibits a resonance phenomenon which is now commonly referred to as spin or paramagnetic resonance. This discovery marked the beginning of a new branch of experimental physics called microwave spectroscopy and thus opened the door to a number of researchers to probe more deeply into the secrets of solid substances and low temperature physics. Ferromagnetism, diamagnetism, and paramagnetism have become better understood as a result of this breakthrough.

Researchers at Oxford University in England, in particular, have been working diligently in this field of microwave spectroscopy from its inception to unlock secrets of solids at low temperatures. While doing this they have catalogued a wealth of information on many paramagnetic substances including two of those now used in Masers. While these researchers gave little thought to how such information could be applied, others were suggesting that microwave amplifiers could result if a paramagnetic crystal could be obtained which exhibited just the right characteristics. From 1952 to 1956 very little serious effort was directed to develop such an amplifier.

In 1956 Professor Bloembergen of Harvard University in a now celebrated paper,[1] suggested the details for the design and development of such an amplifier. He predicted that it would exhibit extremely low noise characteristics. Only a whisper of this latter point was necessary to stir the applied physicists and engineers to test their talents in developing such a component. Microwave amplifiers utilizing paramagnetic crystals, popularly called Masers, were designed and developed first at Lincoln and then at Bell Laboratories. Lincoln Laboratory experimentalists put to rest the $64,000.00 question regarding the Maser's low-noise characteristics soon after the first successful Maser was operating. They determined that the noise output was almost directly proportional to the temperature of the helium bath, and this noise figure at 4°K was less than .1 db. By late 1957 and early 1958 Bloembergen's theories of amplification and low noise were conclusively proved, thus bringing this device from the embryonic to its present adolescent stage.

A new frontier in the art of low noise receivers has been reached and it is only now a matter of watching, partaking, and enjoying the fruits of this preliminary effort.

II PRACTICAL ASPECTS

A. Paramagnetic Resonance

Paramagnetic resonance is based on the fact, just as is ferromagnetic resonance,[2] that when an ion possessing a resultant angular momentum is placed in an applied d.c. magnetic field, the angular momentum vector precesses about the axis of the d.c. magnetic field, at an angular frequency $f = \gamma H$ where $\gamma = 2.8$ Mc/s/oersted for electrons. If a circularly polarized magnetic field (for our purposes, an RF magnetic field) is synchronized with this precession in frequency and direction the ion may absorb energy from the RF field and jump to the next higher energy level. Fig. 1 depicts this situation. On the other hand, if the ion is originally in a higher energy level, it may either drop to a lower level spontaneously or as a result of interaction with the RF field. The important difference between a dilute paramagnetic substance, such as those used in Masers, and a ferromagnetic substance is the number of unpaired electrons per unit volume. In a dilute paramagnetic substance there are only a few such electrons and these are sufficiently far apart that they little affect each other. In a ferromagnetic substance there are a very large number of spins and strong interaction or coupling exists between the spins.

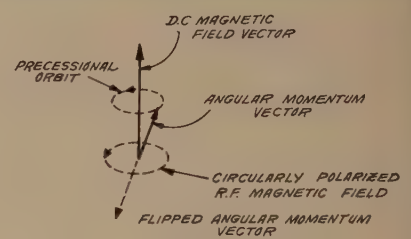


Figure 1

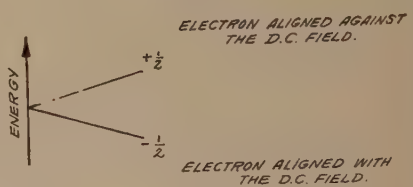


Figure 2

A single free electron has associated with it two energy levels corresponding to two possible orientations in a field and the energy difference between these levels increases as the d.c. magnetic field strength is increased. See Fig. 2. If two free electrons were in-

[1] N. Bloembergen, Phys. Rev. 104, 324 (1956)

[2] See Bowness, vol. 1, No. 1 *Microwave Journal.*

*This paper is devoted to a discussion of the three or more level Masers.

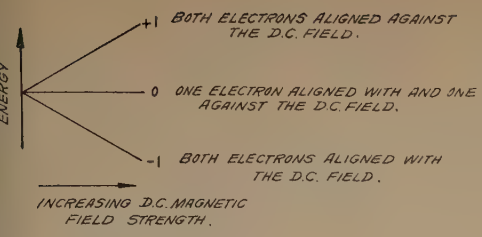

ENERGY
+1 BOTH ELECTRONS ALIGNED AGAINST THE D.C. FIELD.
0 ONE ELECTRON ALIGNED WITH AND ONE AGAINST THE D.C. FIELD.
-1 BOTH ELECTRONS ALIGNED WITH THE D.C. FIELD.
INCREASING D.C. MAGNETIC FIELD STRENGTH.

Figure 3

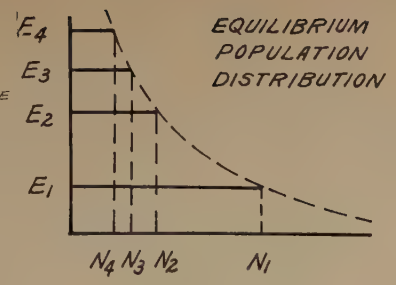


Figure 4

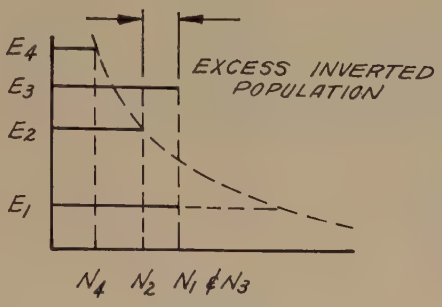


Figure 5

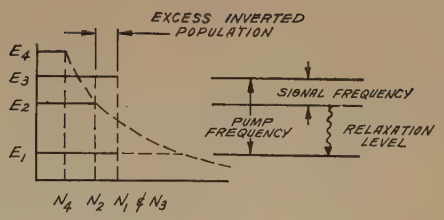


Figure 6

volved there would be three energy levels and the spacings would increase with increasing field as shown in Fig. 3. Three free electrons would provide four energy levels and so on.

B. R-F Frequency vs. Energy Level Separations

The energy that is required to drive an electron from the lower of two energy levels to the higher one is directly related to the frequency by the formula:

$$f = \frac{E_2 - E_1}{h} \qquad (1)$$

where E_2-E_1 is the difference in the energy between the two levels and h is a universal constant, known as Planck's constant. From this formula and the formula connecting the precessional frequency of the "spin-only" momentum vector

$$f = \gamma H \qquad (2)$$

it can be seen that as the d.c. magnetic field is increased, the precessional frequency increases and so also does the energy difference between the levels. Thus it is only necessary to increase the RF frequency accordingly in order to maintain resonance with increasing d.c. field strength. The energy level diagrams pictorially describe these conditions.

C. Number of Electrons in Each Energy Level

In order for a system to have net absorption or emission of energy which occurs when an electron is driven to a higher energy level or when an electron drops to a lower energy level, respectively, there must be a difference in the number of electrons residing in the two energy levels. Under equilibrium conditions, i.e., with no external forces acting on the system, such a state of affairs exists and is described by Boltzmann's distribution function

$$\frac{N_2}{N_1} = e^{-\frac{E_2 - E_1}{kT}} \qquad (3)$$

N_1 and N_2 represent the number of electrons in the respective levels corresponding to the subscripts. The energy associated with level 2 is greater than that of level 1. k is Boltzmann's constant and T is the temperature of the system in degrees Kelvin (absolute scale). Boltzmann's equation describes the fact that more electrons reside in lower energy levels than in upper levels.

From Equation 3, it can be seen that the difference in the populations of two levels increases as the energy spacings increase and also as the temperature is decreased. A graphical presentation of Boltzmann's equation is shown in Fig. 4 for the case of a four spin energy level system.

D. Basis of Maser Operation

The three or more level Maser operates because a population inversion (see Fig. 5) can be achieved. This means that more electrons can be made to reside in the upper of two energy levels than in the lower one. Such a spin system, because it wants to return to the equilibrium state as described by Boltzmann, will give up energy to a small applied RF magnetic field to which the precession of the excess population is synchronized. Such states of equilibrium and nonequilibrium can be compared in Figs. 4 and 5. In a Maser material the unpaired electrons are individually schizophrenic, i.e., each can readily, under proper external stimulation, make jumps from one level to another and these levels need not be adjacent levels. Thus, under a strong stimulation from a source called the pump, it is possible to drive electrons from the first level to the third level directly as shown in Fig. 6 and then under mild stimulation from a signal these electrons can be made to flow back to the second level and give up their energy to this field. With no applied field between levels 2 and 1, the electrons will relax back to the first level at a relatively slower pace giving off the energy to the crystal. They are then ready for their next trip to level 3. In this way a signal can be continuously amplified in a system of this type. The description of the physics has been purposely simplified because it is to be considered more thoroughly in a later section on choice of materials.

Armed with this information the reader can now proceed to consider the problem of designing and testing a Maser typical of the early cavity type.

E. General Design Considerations

The Maser in its earliest forms consisted of a rather high "Q" cavity which supported microwave energy at two different frequencies and in two different modes. It was designed so that cross-talk between the input lines was small. The higher frequency, called the pump frequency, was two or three times that of the lower frequency hereinafter referred to as the signal frequency. A paramagnetic crystal was located in the cavity where the two RF magnetic fields were strong and where a d.c. magnetic field could permeate the crystal rather uniformly. The cavity and associated waveguides which couple the two RF energies into the cavity were immersed in a liquid helium bath. (The materials used then and even today give satisfactory operation only at low temperatures.) The cavity and helium were confined in a dewar flask (thermos jug) and these in turn were surrounded by liquid nitrogen and its dewar flask. (The use of liquid nitrogen is an economy measure. It helps preserve the expensive helium which boils at 4.2° Kelvin). A typical configuration of such a system is shown in

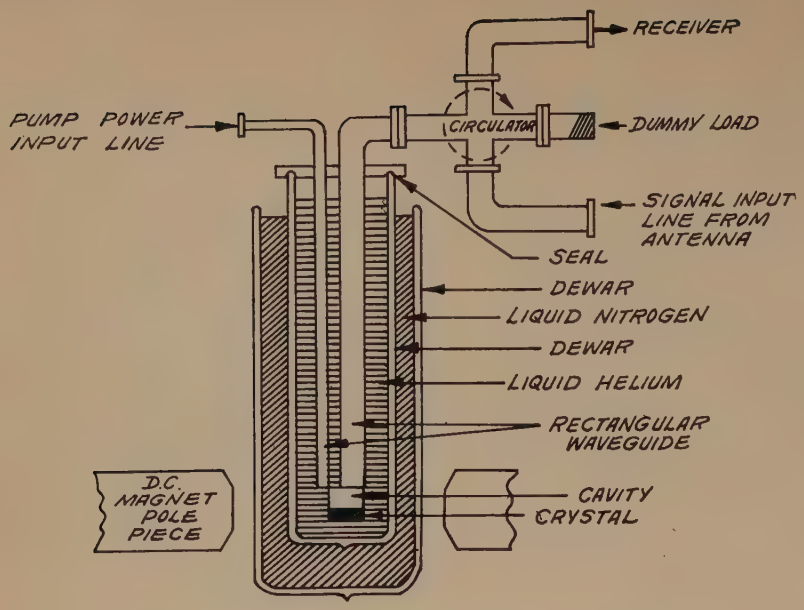


Figure 7

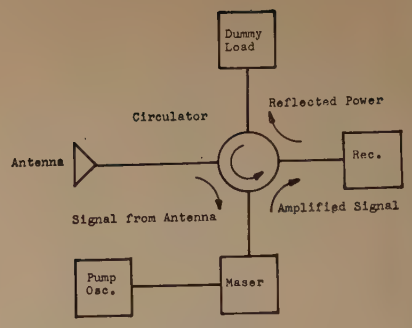


Figure 8

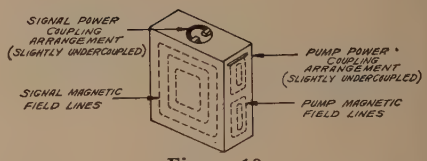

SIGNAL POWER COUPLING ARRANGEMENT (SLIGHTLY UNDERCOUPLED)
PUMP POWER COUPLING ARRANGEMENT (SLIGHTLY UNDERCOUPLED)
SIGNAL MAGNETIC FIELD LINES
PUMP MAGNETIC FIELD LINES

Figure 10

Fig. 7 and includes a circulator for the signal path. Today's Maser cavity designs are quite similar to the earlier ones. A block diagram which describes the signal path is shown in Fig. 8.

Figure 9 shows from left to right a photograph of a stainless steel dewar, a glass nitrogen dewar, a glass helium dewar, a waveguide and cavity system for an X band Maser, and some typical Maser crystals. The cavity field configuration is shown in Fig. 10. The crystals in the foreground are rubies.[3] Those to the left typify boules from which the pieces to the right are cut to fit into the cavity. The two crystals in the rear are chrome doped potassium cobalti cyanide crystals which are typical of those grown in our crystal facility. In the rear is a circulator and to the right is a magnetron magnet modified for use in one of our Maser receiver systems.

F. Other Design Considerations

Because it would be difficult to perform experiments over extended periods of time using the relatively small helium dewars that are available in the laboratory, many precautionary measures are taken to preserve the liquid helium. The waveguides are usually made of thin stainless steel lightly silver plated on the inside only. (Stainless steel has a conductivity approximately one-tenth that of brass.) The helium dewar is usually sealed off from contact with the ambient or room atmosphere and the liquid nitrogen level is maintained. A typical laboratory facility has been described and ours is shown on the cover of the microwave journal.

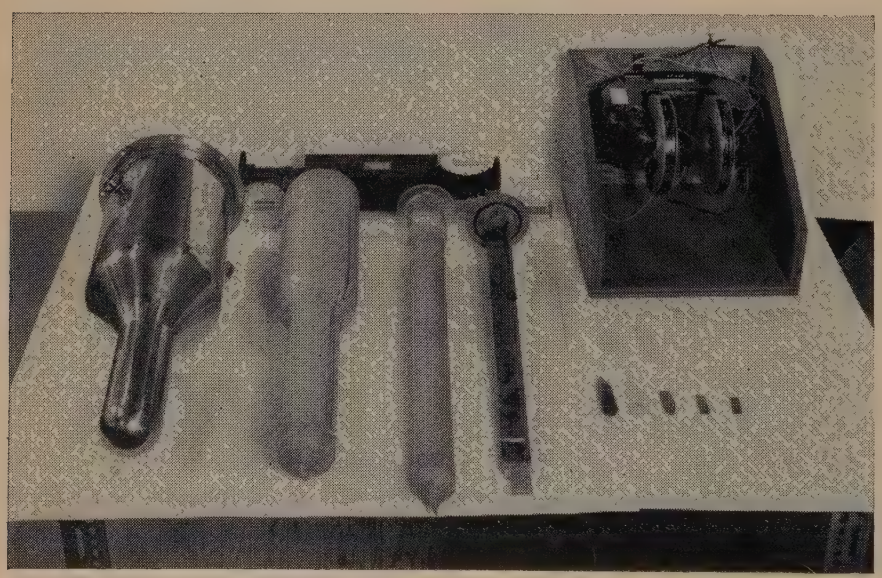


Figure 9

[3]These rubies were purchased from Linde Company.

G. Designing a Maser

Assume that such a test facility is available and you, the experimenter, are required to design a Maser to amplify signals at 6000 Mc/s. Assume further that the crystal to be used is the ruby and that the energy level diagrams are available. Three of such energy level diagrams for different d.c. magnetic field orientations with respect to the crystalline field axis are given in Figs. 11, 12, and 13. The crystalline axis or C-axis is always used as the reference axis. In order to choose the pump frequency it is only necessary to consult the energy level diagrams and make a decision as to the angle and energy levels to be used. As can be seen from the energy levels in Fig. 13 which result from the magnetic field oriented 80° from the crystalline field axis, there are four magnetic field strengths and three different pump frequencies from which a choice can be made. These are indicated on the diagram.

From previous considerations, a larger population difference should result if the situation as indicated by the solid vertical line were chosen. Thus a magnetic field strength of 3500 oersteds and a klystron which can provide a tenth of a watt or so of power at 26,500 Mc/s are required for this choice.

The cavity may now be designed to support the 6000 Mc/s signal and the 26,500 Mc/s pump and tests may then be performed with the active material located in the cavity volume where the RF magnetic fields are reasonably strong and uniform. The system is ready to be tested for operation after the crystal has been oriented and

cut to the desirable shape and size.

H. Preliminary Checks

The resonant frequencies of the cavity are carefully checked in liquid helium to determine the frequency changes due to the change in the linear dimensions and in particular due to the dielectric constant of liquid helium which has filled the cavity. The dielectric constant of liquid helium at 4.2°Kelvin is approximately 1.04. The d.c. magnetic field strength and orientation are adjusted according to the energy level diagram. A sequence of checks are now made to determine whether the pump and signal powers are absorbed simultaneously by the crystal with the given external field configuration. Usually this does not occur on the first attempt and adjustment of the magnetic field is necessary until the two signals absorb simultaneously. The effect of absorption is noted by the rising of the absorption pip on the scope. The resultant change is due to the fact that the reflection coefficient increases due to the change in the impedance of the cavity as absorption increases. Figs. 14A and 14B can be compared for a typical scope presentation. (In all parts of Fig. 14 (.) except the last one, the curve represents the power mode of the klystron as the repeller is swept by a sawtooth voltage.)

I. Test For Maser Action

To test for Maser action, the signal power is reduced sufficiently so that the amplification is reasonably linear in the neighborhood of the signal power level. If the signal is too strong, saturation of levels 2 and 3 may occur and thus amplification cannot result. The signal level may be of the order of 10^{-10} watts for linear simplification.

As the pump power is increased from a very low level, the depth of the absorption pip increases until, as in Figure 14C, critical coupling of the signal line results. At this pump power level the cavity losses are just overcome and any additional power from the pump will result in net gain. Fig. 14D shows a gain of 1. By progressively adding small amounts of pump power, the pip will become inverted and will appear as a spike rising out of the mode characteristic until maximum amplification is reached, at which point additional pump power buys no increase in amplification.

J. Maser Oscillator

To design a Maser oscillator for a 6000 Mc/s signal the experimenter

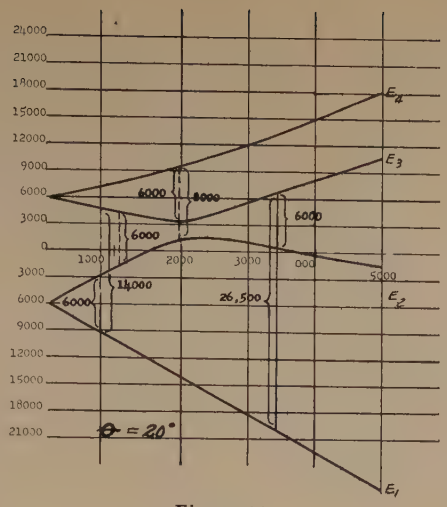


Figure 11

need only reduce the size of the signal coupling hole to the cavity. This reduces the loading and a strong feedback mechanism results with concomitant regeneration. The efficiency is quite low. Note, however, that high frequency oscillators in the millimeter range can be realized by pumping such a Maser system with optical light frequencies. Suitable materials should be available to make this possible.

K. Population of the Levels vs. Oscilloscope Presentation

The population of the electrons in each energy level involved can be described by diagrams which roughly correspond to the cavity mode diagrams given above. In Fig. 5 the electron population of level 1 is decreased and level 3 is populated as pump power is increased. When the population of level 3 is equal to the population of level 2 the case of apparent critical coupling as shown in Fig. 14C results. As the number in level 3 exceeds the number in level 2, amplification results and the pip begins to rise out of the mode characteristic as in Fig. 14D. Pump power is increased until the number in level 3 equals the number in level 1, which corresponds to the state of maximum amplification (Fig. 14E). Additional pump power cannot increase the number of spins in 3 over that in 1.

As this pumping process is taking place, the small applied signal is stimulating the electrons in level 3 to return to level 2 in phase with the signal so that they can give up their energy to the signal. The process is completed when the electrons in level 2 return to level 1 and are then ready for another trip. As the electrons drop from level 2 to 1 they give off their energy to the lattice for it is assumed that the cavity does not support frequencies corresponding to this jump.

If the above procedures are carefully followed a Maser cavity system as described can be made to operate. It appears to be a simple matter and it actually is not difficult to make a Maser system operate, however, this usually is realized only after one has been made to operate. Patience rewarded the first experimenters.

L. Gain Bandwidth Product

The first Maser that one designs usually produces rather unspectacular gain-bandwidth results, and thus it is necessary to analyze Bloembergen's equations carefully in order to achieve optimum results.

The equation governing the gain-bandwidth product of a cavity-type Maser is:

$$G^{\frac{1}{2}}B \simeq \frac{2f_a}{Q_m} \tag{4}$$

where f_a is the frequency of the amplified signal and Q_m is the magnetic Q of the circuit. Q_m is further defined as follows:

$$\frac{1}{Q_m} = \frac{C(N_j - N_i)N\nu}{\Delta\tau} \quad j > i \tag{5}$$

where C is a constant, $N_j - N_i$ is the excess population in level j over that in level i, ν is the filling factor, N is the density of spins per unit volume, and $\Delta\tau$ is the resonance line width of the magnetic material. $(N_j - N_i)N$ ordinarily does not exceed 3% of the total spin population. Thus, in order to improve the gain bandwidth product one may increase the population difference, the filling factor, and the density, and decrease the line-width of the magnetic material as can be seen from these equations.

1. *Increasing the Population Difference*

One of the more obvious ways to increase the population difference between levels 2 and 3 is to increase the equilibrium difference between levels 1 and 3. This latter can be accomplished by choosing the energy levels so that a larger pump frequency can be used which corresponds to an increase in the energy difference of the levels, note Fig. 4. Another method for which Dr. Kikuchi and his group at the University of Michigan are credited is the "push-pull" scheme. In this a set of symmetric energy levels are used as in Fig. 12. The enhancement is due to the fact that if levels 1

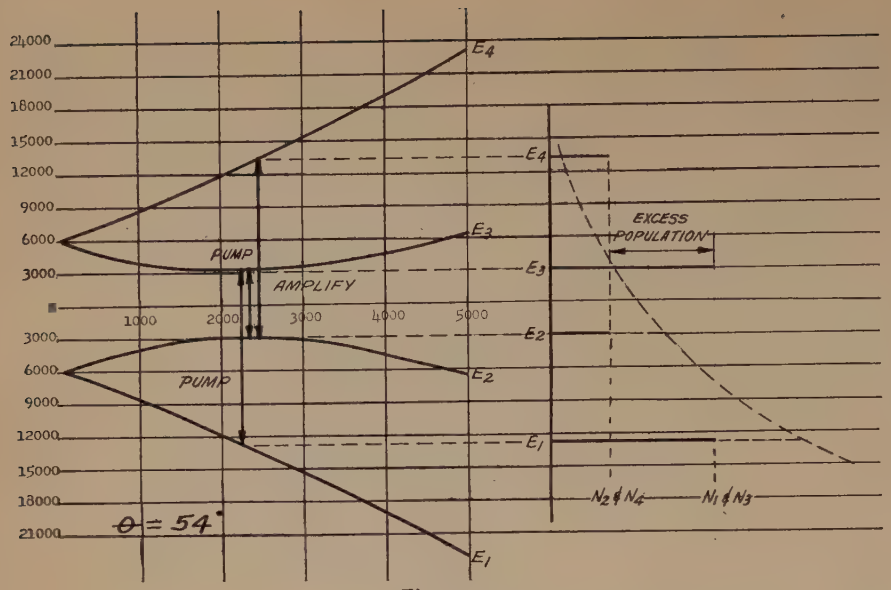


Figure 12

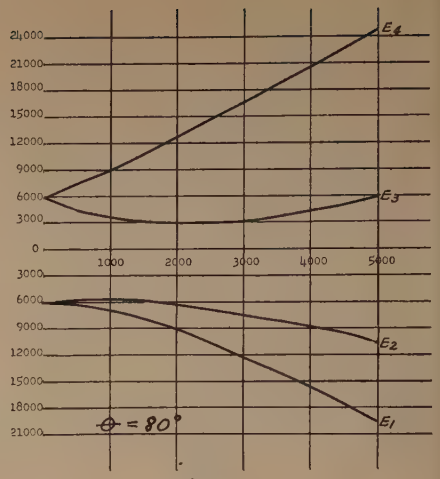


Figure 13

and 3 are pumped so also are 2 and 4, thus the population of level 3 is increased at the expense of level 1 and the number in level 2 is decreased by being pumped to level 4. The electrons relax back from level 4 to 3 and level 2 to 1 and amplify a signal corresponding to the frequency difference of levels 3 and 2. Bell Laboratory personnel in their first Maser used a doping or impurity additive technique to provide an additional path by which the electron could relax back through the spin-lattice process and thus speed up the spin availability. By reducing the temperature of the material a further increase can be achieved.

2. *Filling Factor*

Filling factor is defined as the ratio of the integral of the RF magnetic field in the crystal to that of the cavity. Filling factors of one-tenth or so were realized in the early cavity designs. In general, the fields in a cavity are linearly polarized and it is well known that any linear polarization can be broken up into two counter-rotating circularly polarized waves. Since only one of these can be rotating in the same direction as the precessional motion of the spin, a maximum filling factor of .5 can be achieved. A cavity design rather typical of those used today is shown in Fig. 10.

3. *Material Linewidth and Spin Density*

The half-power linewidth, $\Delta\tau$ is obtained from

$$\Delta\tau \sim \frac{1}{\pi T_s} \qquad (6)$$

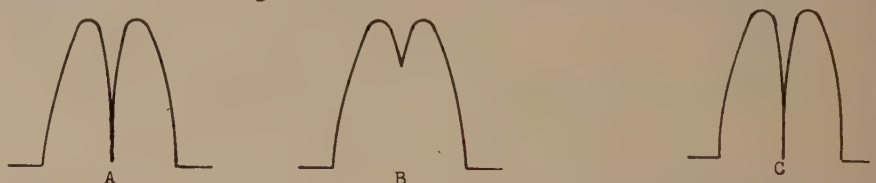
where T_s is the spin-spin relaxation time. (This relaxation time is of the order of 10^{-8} seconds for the ruby.) This linewidth is intimately connected with the number of spins per unit volume, N. As the volume density is increased, a point is reached at which if the volume density is further increased the line width also increases. So there is a practical limit or an optimum density that should be determined for the material. Tests on various percentages of chrome in the host crystal, potassium cobalti-cyanide, are now being conducted at Ewen Knight to determine the optimum doping for this crystal.

4. *Slow-Wave Structure*

In order to achieve large bandwidths, cavity masers with large Q's should be abandoned for the slow or traveling wave structure. Using a traveling wave structure, the bandwidth as a function of gain is given by:

$$B = \left[\frac{1n2}{1n\frac{G_{max}}{2}}\right]^{1/2} \times \frac{1}{\pi T_s} \qquad (7)$$

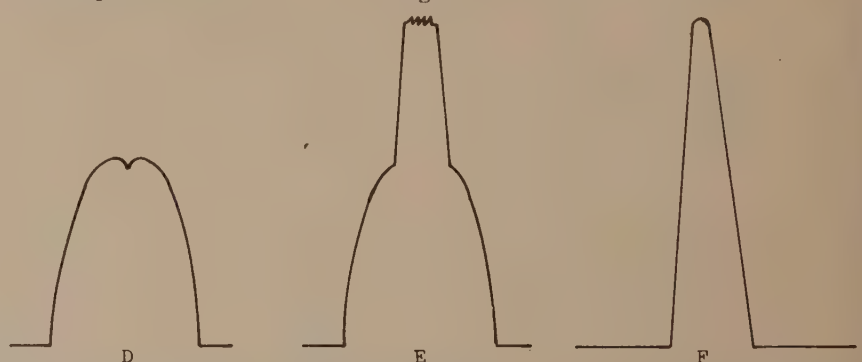
Thus for a gain of 20 db, $B = .42 \times \frac{1}{\pi T_s}$ and for a linewidth of 60 Mc/s



Cavity resonance for the signal as presented on an oscilloscope with the D.C. magnetic field off. Slightly undercoupled condition. Pump is also slightly undercoupled or critically coupled.

D.C. magnetic field is adjusted so that signal & pump powers are absorbed simultaneously. This is indicated by an increase in reflection coefficient for both the pump and signal.

Cavity resonance for small applied signal and pump powers. Losses to the cavity are now overcome and with increased pump power amplification can occur.



Oscilloscope Pattern for a gain of 1.

Large amplification occurs as pump power is increased until crystal saturation occurs at which point maximum gain is achieved.

By reducing the signal coupling sufficiently, the system can be made to oscillate.

Figure 14

which is typical of the ruby, the bandwidth would be 25 Mc/s. This might be achieved in a structure of length 10 inches or so. In a cavity Maser the bandwidth would probably not exceed eight to ten megacycles at X Band unless it acts as a traveling wave structure. Other techniques such as stagger tuning in the slow wave structure can be tried to increase the bandwidth. Typical of the slow wave structures under consideration are the helix and ridged guide structures.

IV CHOOSING MATERIALS

A. Introduction

A paramagnetic substance can be thought of as a material which exhibits a slightly positive magnetic susceptibility. Maser materials, in particular, are ones in which the ions are sufficiently far apart so that the magnetic moment of each is effectively independent of its neighbors, i.e., the active ions only represent a small percentage of the total crystal. As an example, in the first Lincoln Laboratory Maser, the host crystal, potassium cobalti-cyanide, which of course has a zero magnetic moment and acts as a diamagnetic substance, was doped with only one-half of one percent by atomic weight of potassium chromi-cyanide.

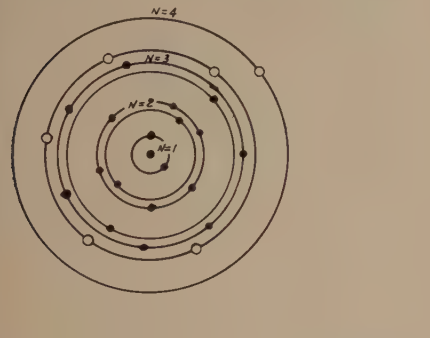


Figure 15

1. *The Number of Energy Levels*

At each site where a chromium atom displaces a cobalt atom, three of the electrons in the unfilled shells as shown in Fig. 15 enter the bonding process and thus three unpaired electrons remain. In this figure the electrons in the unfilled shells are denoted by the clear dots and those in filled shells by the black dots. The three unpaired electrons remaining provide four spin energy levels as shown in Fig. 16. The lowest corresponds to the case in which the three electrons are aligned in the same direction and also are aligned with the d.c. field. This is commonly referred to as the —3/2 energy level because each spin vector has a value of —½ in the direction of the d.c. field. When one of these electrons is flipped in the opposite direction with respect to the applied d.c. field, the resultant vector has a magnitude of —½. It is obvious that the other two levels can be labeled +½ and +3/2 in ascending order. Fig. 17 depicts these spin energy states.

2. *Reason for Complicated Energy Levels*

In an earlier part of this paper, the "spin-only" conditions were discussed and the relation between frequency and the energy level spacings were discussed on the basis of the precessional motion of the resultant angular momentum vector due to a single free spin. This was a very simplified picture for the energy levels which result, which can be seen in Fig. 11, are a function of the crystalline field and lesser electric fields, coupling between the spin magnetic moment and orbital magnetic moment of each electron, coupling between the spin moments of the two different electrons and other smaller magnetic fields and thus nice linearly varying energy levels as shown in Figs. 2 and 3 do not result. Invariably then a large number of low temperature experiments such as the Oxford University group have performed are necessary in order to describe these energy levels as a function of an applied d.c. magnetic field. In view of this, the task of choosing materials would seem impossible if such experimental data were unavailable. This is true, but even without this data for a given crystal it is possible to state general properties the material should possess for satisfactory Maser action.

B. Properties of Materials

Among the electrical properties of significance are: (1) The material must possess a zero field splitting and this splitting should be of the order of the amplifying frequency, (2) For the purpose of this paper the number of spin energy levels must be at least three, (3) There must be a sufficient number of spins involved and (4) The crystal should be single. Other characteristics which may play an important role are:

Dielectric constant
Loss tangent
Thermal conductivity
Mechanical stability

The latter characteristics are rather well understood and no additional explanation is needed.

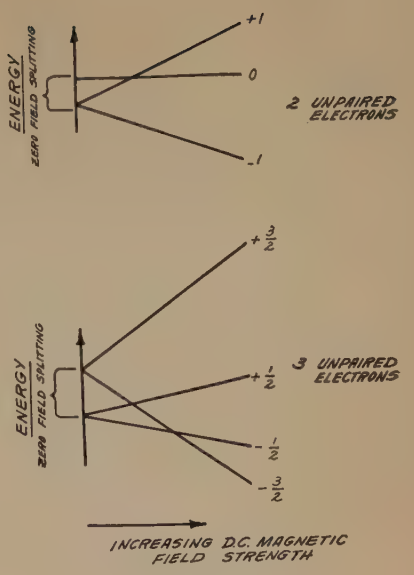


Figure 16

1. *Zero-Field Splitting*

In order to realize the inverted population distribution, as shown in Fig. 5, zero-field splittings are required and these should be of the order of the amplifying frequency. Zero-field splitting is defined as the splitting, or the lifting of the spin energy degeneracy, in the absence of an externally applied d.c. magnetic field. Thus this splitting is due to electric and magnetic fields and their interactions, and these are inherent in the crystal. The crystalline electric field plays an important role and is one of the largest forces serving to split orbital levels and spin levels. The interaction between the magnetic fields associated with the orbital motion and the spinning motion of each unpaired electron also plays an important role. The latter is referred to as spin-orbit coupling or L : S coupling.

In case that the zero-field splitting is zero, an electron would be permitted under proper stimulation to make jumps only to adjacent energy levels or single jumps, as noted in Fig. 2. In a Maser material the electrons in the lowest state, or any other that is occupied, under stimulation of the pump can avoid an adjacent level and can make direct jumps to a third level. That this occurs is due to the scrambling of the energy levels resulting from the zero-field splitting. By comparing Figs. 3 and 16 the reader can intuitively appreciate this. In Fig. 3 the levels are well defined and singular, and in Fig. 16 they are not. For these levels to be well scrambled the reader may be able to satisfy himself that the splitting should be of the magnitude of the signal frequency. In

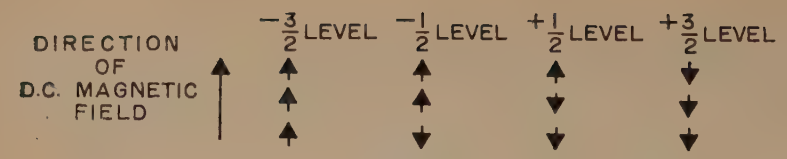


Figure 17

Fig. 11 the zero field splitting of the ruby can be seen to be approximately 12,000 Mc/s so the ruby should be favorable for Maser action for the system described earlier. There is an upper limit to the frequencies which can be amplified, i.e., there is a transition from these scrambled to well-defined states which occurs at high d.c. magnetic field strengths, and in these regions Maser action is not possible. For example, Masers using ruby to amplify signals above, say 20,000 Mc/s, might be difficult to realize.

2. *Number of Energy Levels*

The requirement of at least three energy levels means that two unpaired electrons must remain when the paramagnetic ion is placed in the host crystal. Where a double pump scheme is desired (see Fig. 12), three unpaired electrons are required. The specifications for the levels fairly well defines the impurity and the host crystal to be chosen. For a three level Maser, nickel could suffice if a satisfactory host crystal were available. A four level Maser can be realized using chromium. In the ruby and cyanide crystals three of the outer electrons of the chromium atom are involved in the bonding and three unpaired electrons remain per substitution site. Paramagnetic crystals can also be realized using other elements. Gadolinium ethylsulphate, a rare earth salt, was used at Bell Laboratories and this material has eight energy levels.

3. *Transition Probability As a Function of Mixing of the Levels*

In an earlier section of this paper some obvious methods of increasing the number of spins were discussed. One of the most important not discussed previously is transition probability. In Fig. 5 saturation of levels 3 and 1 are indicated, however, this condition would have to be modified if the 3-1 transition probability were low. In the ruby, for example, the 3-1 transition probability is zero when the d.c. magnetic field is aligned parallel to the crystalline axis and this occurs because in this case the levels are not scrambled. Thus the experimenter should avoid this configuration. Such configurations can be determined by calculation and, of course, by experiment.

4. *Transition Probability As a Function of Spin-Lattice Relaxation Time*

The spin-lattice relaxation time is the time it takes a spin to relax from one level to another in the absence of external stimulation. The energy is absorbed by the lattice. This time cannot be so short that an electron will relax back to its starting position before the external stimulation has taken control nor should it be so long that clogging of the levels occurs. It is inversely proportional to temperature and at 4°K the ruby exhibits a spin-lattice relaxation time of 10^{-2} seconds. This relaxation time has been satisfactory so that Dr. Kikuchi's group at Michigan have been able to realize a bandwidth of 4 Mc/sec at a gain of 20 db using the ruby as an amplifier of 9000 Mc/sec signals. The temperature was 4.2°K. Others have reported improvements while operating at lower temperatures.

To realize satsfactory relaxation times, the orbital angular momentum should be quenched, i.e., the angular momentum should be one of spin only, and the low-lying orbital levels should be sufficiently separated. The iron group elements, such as chromium, meet these requirements while the rare earth materials generally do not.

5. *Necessary and Sufficient Energy Levels*

Another important factor is the number of energy levels competing for the unpaired electrons. The economics dictate that only those levels necessary for Maser operation should be occupied. Materials which exhibit nuclear magnetic moments are to be avoided for these will contribute energy levels in which such electrons may reside. Other orbital energy levels should be far enough removed so that the spin-occupation probability is nil.

6. *Single Crystal*

Another important factor is crystal growth. The crystal should be single so that a definite crystalline electric field can result. Twinned crystals which exhibit major growth habits in two different directions or polycrystalline materials are not satisfactory. See Fig. 18 for a sketch of the potassium cobalti-cyanide unit cell and a large crystal which results from this building block. The crystalline axis is indicated.

IV THE FUTURE OF THE MASER

A. Introduction

This article has been primarily concerned with presenting a short history of the events leading to the development of the Maser and also discussing the design parameters and other facets to clarify its operation. Let us now turn our attention to the facts of life, such as where can the Maser be used effectively, how practical is it, what problems does it create, and finally what can be expected of the research in this field.

B. Applications

For the radio astronomer, a Maser equipped receiver system in the frequency range of 1000 Mc/s to 10,000 Mc/s with a 50 Mc/s bandwidth and 20 db gain means that he can explore many light years further into space than has been possible heretofore. He would be able to detect many new radio stars and could chart them in much the same manner as optical stars have been in the past. A narrower band L band system with 20 db gain would provide him the opportunity to scrutinize the interstellar hydrogen line more carefully so that he can possibly determine the expansion properties of the universe. The scatter communications engineer and others could obtain longer range instruments.

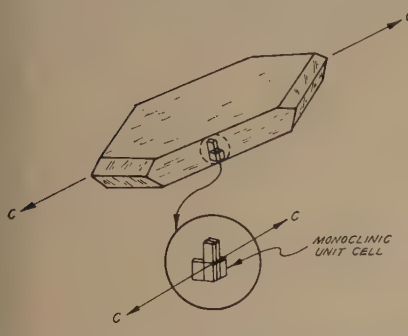
For effective utilization of the low-noise properties of the Maser the device is limited to use in systems which look into backgrounds having the same low-noise characteristics. The sky has a noise temperature of a few degrees Kelvin in the frequency range 1000 to 10,000 Mc/s. As one moves progressively out of this range, the background radiation increases rapidly. See Fig. 19. The earth on the other hand is a 300°K radiator and a Maser system could not be used to advantage to detect small signals in such a background; a system having a 3 db noise figure could be more efficiently used. There is in addition the problem of the magnitude of the signal or background which may be so high to produce nonlinear gains or even saturate the energy levels.

The physicist, of course, can use the Maser as a tool to further his understanding of relaxation processes and other properties.

C. Practical Aspects

This system should not be con-

strued to be representative of a final system. The biggest problem of course is the storage of liquid helium. This problem can be solved with a closed-cycle helium liquifier of reasonable size. This would make possible a small dewar system and thus a small magnet system. These incorporated with a helium gas reservoir and a small nitrogen liquifier spell a practical system which could operate continuously



SINGLE CRYSTAL OF POTASSIUM (CHROMI-COBALTI) CYANIDE

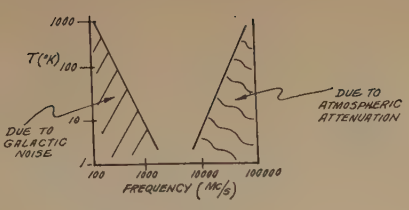
Figure 18

for a number of weeks or months with a minimum of service and a reasonable space requirement.

D. Exposure of Other Weak Links

Until the development of the Maser the low-noise receiver system weak link was the microwave mixer. Today, the waveguide components preceding the mixer or the Maser represents the weak link blocking the realization of a very low-noise receiver system. These components, antenna, ferrite switch, circulator, and waveguide run contribute ordinarily 2 to 3 db of loss to the signal and this represents a noise temperature of 180 to 300° Kelvin (.1 db = 7°K for F < ¾ db) and, therefore, this must be reduced in order to take advantage of the 4° to 10°K noise figure of a Maser. Our laboratory, for example, has established a ferrite components and a materials group to develop materials and design components for use in passive receiver systems and especially for use in Maser receiver systems. Thus receiving systems with ultimate noise figures of .2 to .8 db should be realized.

There is still the question of gain stability. Even with the Maser's low-noise characteristics if its gain stability is poor the usefulness of the device in such instruments as high sensitivity radiometers could be nil. In the Ewen Knight Laboratory a special versatile receiver has been developed which will permit a comparison of receiver sensitivity in which the first amplifier can be a Maser, a



EFFECTIVE BACKGROUND RADIATION Vs. FREQUENCY

Figure 19

parametric amplifier, or a TWT amplifier.

E. Research Efforts

The research efforts are today concentrated in (1) Studying methods of increasing gain bandwidth products using ruby and cyanide materials and (2) Developing new Maser materials.

Some of the design research is concerned with determining the optimum configuration of the cavity system as a function of the relative orientations of the three magnetic fields. Other experimental work is being carried out to determine the optimum percentage of doping and optimum shape and size of crystals. These efforts are mainly for the purpose of increasing the gain bandwidth product. Recently, for example, Ewen Knight achieved a 3 Mc/s bandwidth and 15 db gain Maser which amplified a 2800 Mc/s signal using th chromi-cyanide crystal. This is a factor of 2 or 3 greater than that as yet known to the author. The volume of the material was less than .1 the volume of the cavity. Also, an X band Maser with a 16 Mc/s bandwidth and 16 db gain was recently developed at Ewen Knight.

In the materials research efforts the author is not aware of the development of any new materials which appear to be improvements over the ruby and cyanide crystals. Certainly, it would seem reasonable to expect that as the knowledge of the internal processes become better understood and as the experimental data is made available on paramagnetic crystals one will need only consult a catalogue for a proper Maser crystal for use at a given frequency and operating temperature range in much the same manner as microwave mixer crystals are today.

F. Conclusion

It is interesting to reflect on what the status of the Maser and the field of paramagnetics would be today, especially in this country, had development of the diode or parametric amplifier preceded that of the Maser chronologically. Certainly one may say that the wonderful research that is now going on in this field of solid state physics and the deserving concentrated attention it is now receiving would not have been possible had the time capsule been reversed.

The author wishes to thank his coworkers Drs. Rizzi and Knight and Mr. Dominick and Mr. Wenckus for their timely discussions and their valued criticism.

Special thanks are due the secretary, Miss Vincola, for her untiring efforts to complete this article on time.

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Microwave Properties and Applications of

FERRITE ROTATORS

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SUMMARY

The theory of Faraday rotation is presented. The rotation and loss properties of ferrite cylinders in circular waveguide structures are discussed. Bandwidth and power handling problems and possible solutions are also discussed. Finally, some microwave applications of ferrite rotators are described and a few of the design considerations indicated.

INTRODUCTION

IN 1845, Michael Faraday performed the following experiment in an attempt to show that light was electromagnetic in nature. He passed a beam of linearly polarized light through a plate of glass that had been placed in a strong magnetic field. He observed that when the field was aligned parallel to the direction of light propagation, the plane of polarization of the beam was rotated as it passed through the glass. Further experiments showed that the amount of rotation was a function of the magnetic field strength and the thickness of the glass. He also noticed that if the direction of propagation was reversed relative to the direction of the magnetic field, the sense of rotation was also reversed. Hence this effect, the so-called Faraday rotation effect, is *nonreciprocal*. Other investigators performed the same experiment using very thin layers of magnetized iron. Rotations of up to 500,000 degrees per inch were realized.

Although this phenomenon was rather interesting, it did not take on practical significance in the field of communications until the recent development of ferrites. Ferrites are derived basically from magnetite, an iron oxide found in nature as a mineral. The ferrite is obtained by replacing some of the iron atoms in the magnetite structure by other metallic atoms such as manganese, zinc and nickel. The resulting material exhibits good magnetic properties and yet its resistivity is from 10^6 to 10^{12} times higher than ordinary magnetic materials. Because of these properties, ferrites have very low eddy current losses and consequently are being used to great advantage in the design of high frequency filter coils, antenna rods and pulse transformers. A fact of even greater importance to the microwave engineer is that due to the high resistivity of the ferrite, a material is now available which is magnetic and yet transparent to electromagnetic waves. Because of these properties, attempts were made to observe the Faraday rotation of electromagnetic waves in the microwave region. These experiments were successful with rotations of up to 150 degrees per inch being observed.

THEORY OF THE FARADAY ROTATION EFFECT

Electromagnetic Properties of the Ferrite

An electron model that is often used to explain the Faraday Rotation Effect is shown in Figure 1. The small sphere represents an electron spinning about its own axis with an angular velocity ω_s and having an angular momentum J. In addition to its mechanical momentum, the electron also possesses a magnetic moment m since it has charge and is spinning. Hence one can think of the spinning electron as a tiny magnet which is magnetized in the direction of the vector m. Now, when a magnetic field (H_a) is applied in the z-direction, there is a torque on the electron which tends to align the "tiny magnet" (the vector m) with the magnetic field. However, since the electron has mass and is spinning with an angular velocity ω_s, it acts like a gyroscope. That is, instead of aligning itself with the magnetic field, it tends to precess about the z-axis as shown in the figure. The precession frequency ω_p depends upon the strength of the magnetic field H_a. If the field is strong, the torque on the electron is large, and the precession frequency is high. Thus

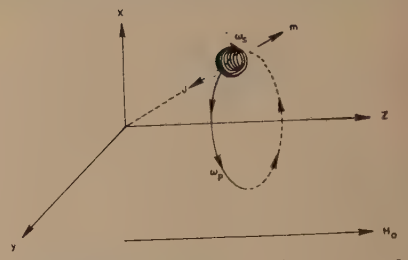

Figure 1 — The spinning electron model representation.

it is seen that the natural frequency of the precession is directly proportional to the magnetic field. Neglecting demagnetizing effects, the natural frequency is 2.8 megacycles per oersted of magnetic field. For example, a field of 3000 oersteds would cause a precession at 8400 megacycles.

As in any resonant system, if no losses were present, the precession would be sustained indefinitely. However, since losses are invariably present, the precession is damped in a matter of a few millimicroseconds. In order to sustain the precession, energy must be supplied to the system at the natural resonant frequency. If a circularly polarized microwave signal is applied to the system so that its sense of rotation is the same as the precession of the electron, the wave, through its r-f magnetic field, will supply energy to the electron so as to sustain the precession. In other words, a material containing many of these spinning electrons (viz., a magnetized ferrite) will appear very lossy to the circularly polarized wave described above. However, if the microwave signal is circularly polarized in a sense opposite to that of the precession, the net energy supplied to the ferrite's resonant system will be zero. That is, since the wave is trying to precess the electrons in a direction opposite to their natural precession, the system does not accept this energy and thus, the net transfer

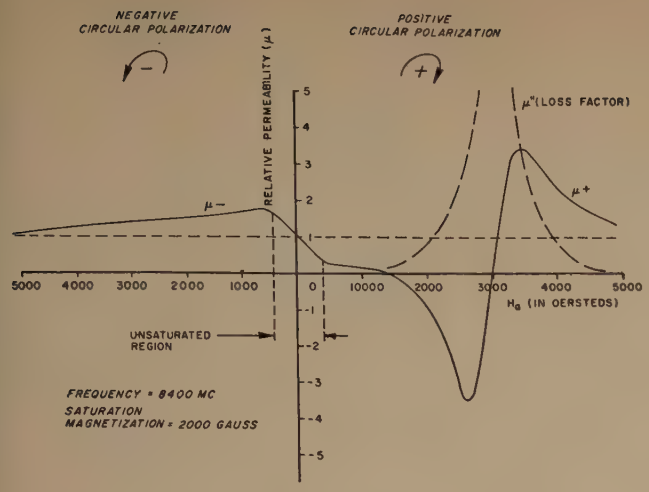

Figure 2 — Microwave permeability of a typical ferrite.

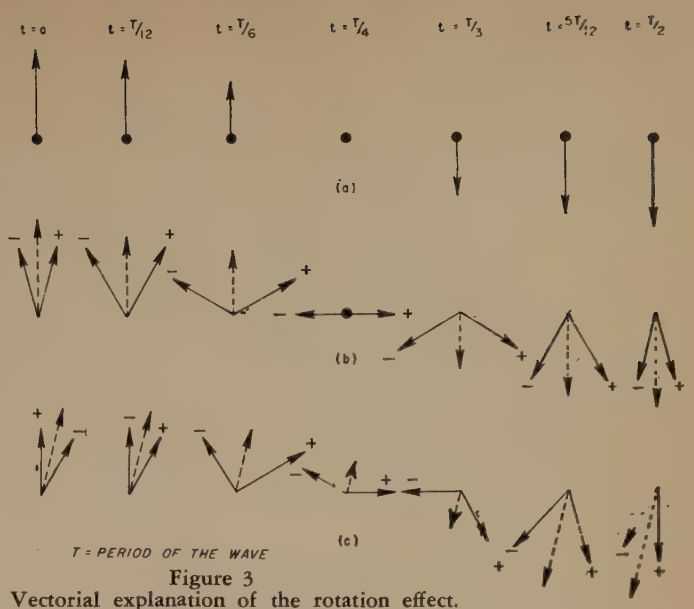

Figure 3
Vectorial explanation of the rotation effect.

of energy from the microwave signal to the ferrite is zero. Consequently, for this sense of circular polarization, the ferrite appears transparent. The important fact to note is that the magnetized ferrite reacts differently to the two senses of circular polarization.

Although this difference is most apparent at the resonant frequency, it is still noticeable at frequencies far removed from it. At these frequencies, however, the major difference is in the velocities of the two circularly polarized waves in the ferrite, whereas at resonance the major difference is in the loss characteristics. Since these effects are due to the magnetic properties of the ferrite, they should be reflected in the r-f permeability of the ferrite. Figure 2 shows a typical curve of r-f permeability as a function of magnetic field and for the two senses of circular polarization. For zero applied field, the permeabilities for the two waves are the same. As the field is increased, the permeability for the negative wave ($\mu-$) increases while the permeability for the positive wave ($\mu+$) decreases. Near resonance (3000 oersteds in this case) $\mu-$ is practically constant while, as expected, $\mu+$ has a very large variation. Similarly the loss factor, as indicated qualitatively by the dotted line, is very large at resonance but small elsewhere.

Explanation of the Faraday Rotation Effect

Having presented some of the electromagnetic properties of the ferrite, it is now possible to explain the Faraday Rotation Effect. As stated previously, the effect is that the plane of polarization of a linearly polarized wave is rotated when passed through a magnetized ferrite. A linearly polarized wave is defined as one in which the orientation of the field vectors is independent of time. Figure 3a shows a linearly polarized wave at several instants of time. Note that the magnitude varies but the orientation is constant. It is also important to note that such a linearly polarized wave can be considered as being composed of two circularly polarized waves equal in magnitude but rotating in opposite directions. This can be verified by referring to Figure 3b where the two circularly polarized waves (denoted by + and —) can at all times be combined to yield the linearly polarized wave shown in Figure 3a.

Now, what happens when a linearly polarized wave passes through the magnetized ferrite? If the field applied to the ferrite is well below the resonant magnetic field, the two circularly polarized components of the input linear wave pass through the ferrite with negligible loss. However, as stated earlier, the two components experience different phase shifts since in one case (+ wave) the wave tends to aid the precession of the spinning electron while in the other case (— wave) it tends to oppose the precession. Suppose, for example, the — wave is phase-delayed 30 degrees with respect to the + wave. This means that all the minus vectors in Figure 3b are retarded by 30 degrees. This is shown in Figure 3c. Combining the circularly polarized components, one can see that the result is a linear wave where the plane of polarization has been rotated 15 degrees. Thus, it is seen that the Faraday Effect can be explained in terms of the following facts: 1) a linearly polarized wave can be decomposed into two counterrotating circularly polarized waves and 2) the phase shift through the magnetized ferrite is different for the two senses of circular polarization.

Faraday Rotation in an Infinite Ferrite Medium

For the example chosen above, a phase difference of 30 degrees led to a rotation of 15 degrees. By use of Figure 3, it can easily be deduced that the rotation (θ) is equal to one half the difference between the phase shifts of the circularly polarized waves. That is

$$\theta = \frac{\phi- - \phi+}{2} = \frac{\beta- - \beta+}{2} L \qquad (1)$$

where $\beta+$ and $\beta-$ are the phase shift per unit length for the + and — waves, respectively.

Since from plane wave theory $\beta = \frac{\omega}{c}\sqrt{\mu\epsilon}$, one obtains for the case of a plane wave in an infinite ferrite medium magnetized in the direction of propagation

$$\theta = \frac{\omega\sqrt{\epsilon}}{2c}(\sqrt{\mu-} - \sqrt{\mu+})L \qquad (2)$$

where

ω = angular frequency of the wave (radians per second)

ϵ = dielectric constant of the ferrite

L = length of the magnetized ferrite (centimeters)

c = velocity of light (3×10^{10} centimeters per second)

$\mu+$ and $\mu-$ = r-f permeability of the ferrite (see Figure 3)

If, as in most rotator applications, the ferrite is operated with a field well below the resonant field, then

$$\sqrt{\mu-} - \sqrt{\mu+} \approx \frac{2.8 \times 10^6 \, M}{f} = \frac{2\pi \, (2.8 \times 10^6 \, M)}{\omega} \qquad (3)$$

where M is the magnetization of the ferrite. The magnetization is defined as the magnetic moment per unit volume due to the summation of all the electron magnetic moments (m).

Equation 3 states that the difference between the square roots of the r-f permeabilities is directly related to the magnetization of the ferrite and inversely related to the frequency of the microwave energy. Since the rotation effect is due to the magnetic properties of the ferrite, one would expect it to be proportional to the magnetization of the ferrite. Figure 4 shows a typical curve of rotation versus magnetic field. As the applied field is increased, the magnetization of the ferrite increases and hence the rotation increases until the ferrite becomes saturated. That the difference in permeabilities is inversely related to the frequency, is due to the fact that the field applied to magnetize the ferrite is much less than the resonant field. For example, if a field of 100 oersteds is applied to the ferrite, the resonant frequency of the electron precession will be (2.8) (100) = 280 megacycles. Since the applied signal is in the microwave region, the frequency of the wave will be much greater than the resonant frequency. As stated earlier, the greatest difference in the effect on the two circularly polarized waves occurs at the resonant frequency. Therefore, if the signal frequency is increased, the ferrite is operated even further from its resonant frequency and consequently the difference between the two waves

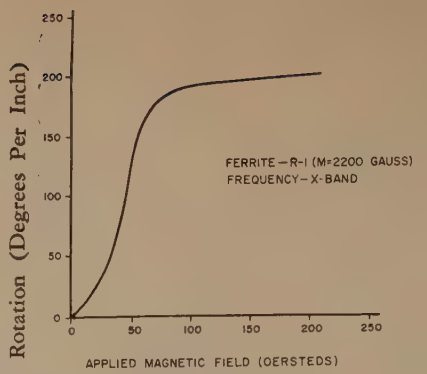

Figure 4 — Dependency of rotation upon the applied magnetic field.

becomes less. This is reflected in the statement of Equation 3. If Equations 2 and 3 are combined, one obtains

$$\theta \approx L \frac{\sqrt{\epsilon}}{2c} 2\pi \, (2.8 \times 10^6) \, M \qquad (4)$$

where

θ = rotation (radians)

L = length (centimeters)

$c = 3 \times 10^{10}$ (centimeters per second)

M = magnetization of the ferrite (gauss)

Equation 4 states that the rotation of the polarization of a plane wave passing through a ferrite medium magnetized in the same direction as that of the wave propagation is directly proportional to the length of the medium and the magnetization of the ferrite. Also, reflected in the statement of Equation 4 are the facts that

1. The rotation is directly proportional to the square root of the dielectric constant of the ferrite medium.
2. If the signal frequency is reasonably high compared to the resonant frequency, the rotation is independent of the frequency of the microwave energy.

As will be seen in the next section, many of the effects observed in waveguide structures can be explained with the help of Equation 4, although it was derived from an infinite plane wave analysis.

FERRITE ROTATION IN WAVEGUIDES

To obtain Faraday rotation in a waveguide containing a magnetized ferrite, the guide structure must be capable of propagating circularly polarized modes. That is, the cross section of the guide must be circular, square, etc. In addition, the ferrite must be situated in a region where the E and H fields are transverse to the direction of propagation. Such a structure is shown in Figure 5a. The ferrite rod is situated in the center of the circular guide and is supported by a low-loss dielectric holder. Figure 5b shows the approximate field pattern in the structure. The pattern is that of a modified TE_{11} circular guide mode.

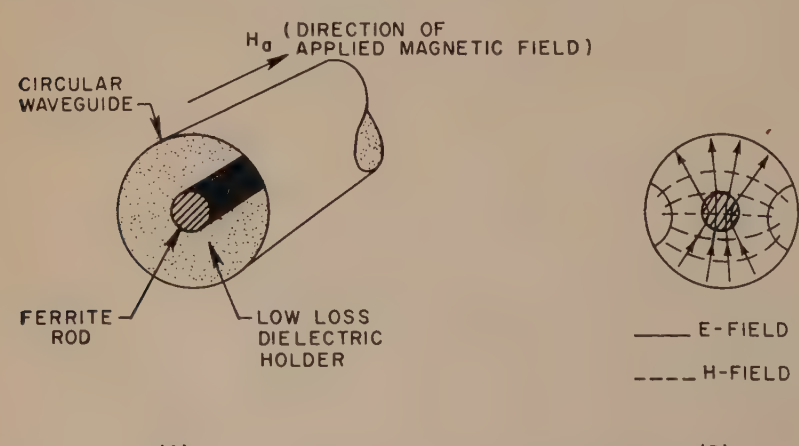

Figure 5 — A typical ferrite rotator structure with its approximate field pattern.

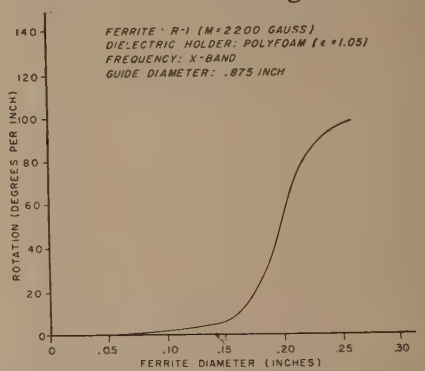

Figure 6 — Rotation versus ferrite diameter data at X-band.

If a linearly polarized wave is applied to the structure shown in Figure 5a, the plane of polarization of the output wave will be rotated due to the Faraday Effect. Given that the longitudinally applied magnetic field is sufficient to saturate the ferrite, the rotation per unit length will be a function of the saturation magnetization of the ferrite, the effective dielectric constant of the medium and the amount of ferrite-loading in the structure. Qualitatively speaking, the term ferrite-loading means the extent to which the properties of the ferrite are reflected in the overall characteristics of the structure. For example, if very little of the r-f energy propagates through the ferrite rod, one would expect the rotation per unit length to be quite small. That is, the ferrite-loading in this case would be small. One method for increasing the ferrite-loading is to increase the ferrite diameter. Figure 6

shows a curve of rotation per unit length versus ferrite diameter for a typical X-band ferrite. For ferrite diameters up to about 0.15 inch, the rotation increases as the square of the diameter. That is, the ferrite-loading is proportional to the cross-sectional area of the ferrite rod. Above this value, the rotation increases quite rapidly. This is due to the fact that the microwave energy in the ferrite and consequently the ferrite-loading increases rapidly as the ferrite diameter is increased.

Rotation and Loss in Circular Guide Rotators

In practice, a usual requirement is to minimize the size of the rotator device. Thus, a desirable objective would be to maximize the rotation per unit length in a given structure. In addition, most applications require that the insertion loss of the device be small. Consequently, one would also like to choose the structure with the lowest loss per degree of rotation. Although these requirements are not always compatible, various microwave techniques can be used to strike a good compromise.

One method of increasing the rotation per length of the structure shown in Figure 5a would be to increase the ferrite diameter further. However, the loss increases even faster and hence, the loss per degree of rotation increases. Further increase in the ferrite diameter also leads to higher order mode propagation which usually manifests itself as a large variation in loss for a small change in the microwave frequency.

Another method of increasing the rotation is to use a holder that has a high dielectric constant. Figure 7a shows the rotation and loss characteristics when rexolite ($\epsilon = 2.5$) is used as the dielectric holder. This material has an extremely low dielectric loss and consequently does not contribute appreciably to the overall insertion loss of the structure. The rotation curve in Figure 7a shows a marked increase in the rotation per unit length over that obtained in the ferrite and polyfoam structure. This increase can be explained by referring to Equation 4. This equation shows the rotation to be a function of the dielectric constant of the medium. In the composite structure of Figure 5a, this refers to a weighted average of the dielectric constants of the ferrite ($\epsilon = 13$) and the

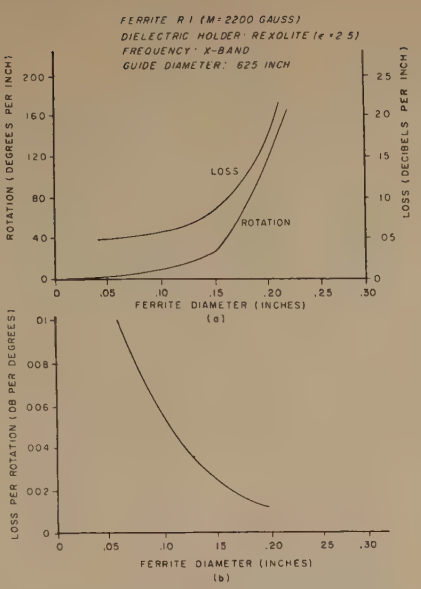

Figure 7 — Rotation and loss properties in a composite ferrite and rexolite structure.

holder. By increasing the dielectric constant of the holder, this average or effective dielectric constant has been increased and consequently the rotation per unit length has increased. If the dielectric constant of the holder is made too large, however, the rotation can actually decrease. This is due to a change of the energy distribution in the waveguide. That is, an increase in the dielectric constant of the holder results in a greater concentration of the microwave energy in the holder. This decreases the ferrite-loading and consequently decreases the rotation. In practice, one usually uses a holder with a dielectric constant between two and six.

At X-band the loss in the composite ferrite and dielectric structure is quite small. Figure 7a shows a loss versus diameter curve for the case of a ferrite rod embedded in a rexolite holder. Combining the loss and rotation data in Figure 7a, one can plot a curve of loss per rotation versus ferrite diameter (Figure 7b). This curve appears to approach a minimum at a ferrite diameter of 0.20 inch. Thus if minimum insertion loss is an important consideration in the design of the rotator device, one should use the 0.20 inch diameter ferrite. If, for example, the device requires 90 degrees rotation for its operation, the insertion loss will be $(.0014) \times (90)$ or less than 0.13 db.

The Low Frequency Rotator Problem

From the above data, it appears that the problem of designing low-loss rotator devices at X-band is quite simple. At higher frequencies the problem is still relatively easy. At the lower microwave frequencies, however, the task becomes increasingly difficult. This is due to the nature of the loss mechanism in the ferrite. The loss in the ferrite is due to both its dielectric and magnetic properties. The reduction of dielectric losses can usually be accomplished by careful preparation of the ferrite material. The magnetic losses, however, are another problem. As stated earlier, the magnetic field applied to a ferrite rotator should be much less than the field required for ferromagnetic resonance. If the rotator is being operated at X-band, Figure 2 indicates that the applied field should be less than, say, 1000 oersteds. If, however, one wishes to operate the rotator device at 1000 megacycles, the resonant field would be 350 oersteds and consequently the field applied to the ferrite should be less than, say, 100 oersteds. Since it usually takes a few hundred oersteds to saturate the ferrite, the device will be forced to operate with a higher insertion loss. In addition, since the ferrite has a loss peak at zero field, the level of attenuation is increased still further. The problem of higher loss at lower frequencies is described qualitatively in Figure 8. At high frequencies the region of low loss is quite broad. At low frequencies, however, the loss minimum below resonance is higher and the range of fields for which low-loss operation can be obtained is quite small.

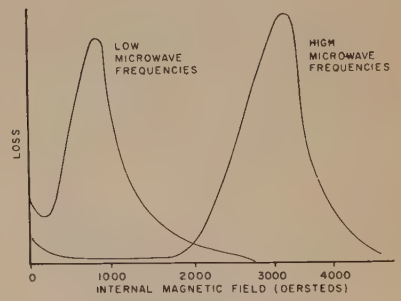

Figure 8 — Frequency sensitivity of the ferrite loss versus magnetic field.

One possible solution is to operate the device well above ferromagnetic resonance. However, this has two disadvantages: 1) the rotation per unit length is less and 2) the magnet required to obtain such a longitudinal field is quite large. Another approach to this problem is to use a ferrite with a very narrow linewidth (i.e., a very sharp resonance peak). The effect of the narrow linewidth is to reduce the loss minimum and to increase the range of fields below resonance for

Ferrite Composition	*Saturation Magnetization*	*Line Width*	*Useful Frequency Range for Rotator Applications*
Nickel Ferrite	3200 gauss	500 oersteds	above 7000 Mc
Nickel-Cobalt Ferrite	3000 gauss	200 oersteds	above 5000 Mc
Manganese-Magnesium Ferrite	2200 gauss	350 oersteds	above 4000 Mc
Yttrium Iron Garnet	1700 gauss	50 oersteds	above 1000 Mc
Single Crystal Yttrium Iron Garnet	1700 gauss	10 oersteds	above 200 Mc

Table 1

which low-loss operation can be obtained. By using this technique, ferrite rotator devices using 90 degrees rotations have been built at S-band with an insertion loss of less than 1.0 db.

A list of some of the better ferrites and their useful frequency range is given in Table 1.

In rotator applications the useful frequency range of the nickel ferrite is limited due to its large line width and high zero field loss (due in part to its high saturation magnetization). The nickel cobalt ferrite is slightly better because of its narrower line width. Despite its larger line width, the manganese magnesium ferrite is even better. This is due to its low zero field loss at frequencies above approximately 4000 Mc.

At frequencies below 4000 Mc another problem arises in the use of ferrites in rotator applications. As stated earlier, ferrite rotator devices usually are operated well below the ferromagnetic resonance field. For the case of an infinite ferrite medium the resonant frequency is 2.8 times the applied magnetic field. However, the relation between the applied field and the resonant frequency is actually a function of the ferrite geometry. For example, in the case of a long cylindrical rod, which is the usual rotator geometry,

$$f_r = 2.8\left(H + \frac{M}{2}\right) \qquad (5)$$

where f_r is the resonant frequency (in megacycles)

H is the applied magnetic field (in oersteds)

M is the saturation magnetization (in gauss)

If one wished to use an yttrium iron garnet at say 2800 Mc, the field required for ferromagnetic resonance would be

$$H = \frac{2800}{2.8} - \frac{1700}{2} = 150 \text{ oersteds.}$$

Since a magnetic field of about 150 oersteds is usually required to saturate the ferrite, it would be impossible to saturate the ferrite and yet operate below ferromagnetic resonance. Therefore, in order to use a long rod of high magnetization material in rotator applications at frequencies below say 4000 Mc, one must operate the ferrite above ferromagnetic resonance. If, however, one uses a very thin disc of ferrite, operation below resonance is possible at the lower frequencies.

For a thin disc the resonance condition is:

$$f_r = 2.8\ (H - M) \qquad (6)$$

Assuming that the internal field required to saturate the disc is 150 oersteds, the applied field required is 150 plus that needed to overcome the demagnetizing field. Therefore, for a thin disc

$$H_{sat} = 150 + M$$

and hence

$$f_r = 2.8\ (150) = 420 \text{ Mc}$$

Since this condition is independent of magnetization, a high magnetization, narrow line width material (e.g., an yttrium iron garnet) of the thin disc geometry can be used at frequencies as low as say 1000 Mc.

A third solution to this problem involves using a narrow line width material with *low* magnetization. A nickel cobalt aluminate ferrite can be made to have these characteristics. If, for example, a long rod of a 400 gauss material is used, then from Equation 5,

$$f_r = 2.8\ \left(150 + \frac{400}{2}\right) = 980 \text{ Mc}$$

where the field required to saturate the ferrite is again assumed to be 150 oersteds. Hence the material can be used in rotators at frequencies above approximately 2000 Mc.

The solution to the low frequency problem is not a simple one. It depends upon not only the line width of the ferrite material, but also its magnetization, geometry and low field loss.

Bandwidth of Ferrite Rotators

At the end of the last section, it was concluded that if the signal frequency was reasonably high compared to the resonant frequency, the rotation would be independent of the microwave frequency. In waveguide configurations this, in general, is not true. For example, the structure shown in Figure 5a is quite frequency sensitive when the dielectric holder is air or polyfoam. At X-band, the rotation varies by 100% over a 10% frequency range. The reason for this frequency sensitivity is that the large difference in dielectric constant between the ferrite and the polyfoam causes the energy distribution in the guide to change radically when the frequency is varied. As the frequency increases, the energy in the ferrite ($\epsilon = 13$) and consequently the rotation increases sharply. One method of improving the situation is to use a holder with a higher dielectric constant. With a holder of dielectric constant $\epsilon = 4$, the rotation sensitivity can be reduced to about 25% over a 10% frequency range. If higher dielectric constant materials are used to reduce the frequency sensitivity, the loss of the device usually increases.

Another method that is quite useful in reducing the frequency sensitivity of the rotator section is the use of three concentric dielectrics. The solid ferrite rod is placed at the center of the structure. Its diameter is chosen to give the required rotation per unit length. Next, the ferrite is surrounded by a very low-loss dielectric material (e.g., Teflon or Rexolite). Finally, a ring of high dielectric constant material (e.g., Stycast K-12) is placed at the outer periphery of the structure. This configuration keeps the percentage of energy in the ferrite relatively constant over the frequency range. As stated above, the absence of the high dielectric constant ring would cause the energy in the ferrite to increase as the frequency increased. The ring of high dielectric constant material has the opposite effect. As the frequency increases the energy in the ring tends to increase which means that the energy at the center of the guide is reduced. Since this is where the ferrite is located, the rotation would tend to decrease. By proper choice of the inside diameter and the dielectric constant of the ring, the two effects can be made to cancel and thus result in a flat rotation versus frequency curve.

Using this technique, one can construct a rotator with a variation in rotation of less than 5% over a 10% frequency range.

A third method of broadbanding the rotation is to use a circular ridge guide which contains two pairs of radial ridges oriented at 90 degrees with respect to one another. The ferrite rod is placed at the center of the guide and is held in place by the four ridges. The two pairs of ridges are required in order to have the two orthogonal planes needed to support the ferrite rotation. The idea in this structure is that the ridges will tend to keep the energy at the center of the guide at all frequencies and thus the rotation will be insensitive to any frequency changes. Such a device has been built with less than a 10% change in rotation over a 20% frequency range.

Finally, it should be noted that in designing broadband rotators, each end of the ferrite structure must be well matched to the adjacent guide. If this is not done the resulting multiple reflections will cause large variations in the rotation versus frequency curve. For narrow band applications, circular matching irises are usually sufficient. In broadband applications, however, dielectric tapers or steps are necessary.

The High Power Problem in Rotators

Another problem which usually arises in the design of a ferrite rotator structure is that of power handling capability. As with all magnetic materials, ferrites have a Curie Temperature. This is the temperature above which the thermal agitation in the material causes it to lose its magnetic properties. Now if the microwave power propagating through the ferrite-loaded waveguide is very high, the losses in the structure will cause the temperature of the ferrite to rise above its Curie point. Thus the ferrite will lose its rotation properties and the device will not operate properly. An obvious solution to this problem is to use forced cooling and, in fact, this method is often used in practice. Whether or not this method is used, the design engineer should, in high power applications, optimize the microwave structure from a power handling point of view. In general, the approach is to keep the losses to a minimum and provide a good conducting path for the heat generated in the ferrite. For the structure shown in Figure 5a, this means that (1) the ferrite loss per dissipative area should be minimized and (2) the dielectric chosen as a holder should have good heat conducting properties as well as low microwave loss (e.g., quartz). Since the dissipative area of the rod increases in proportion to its diameter while the losses increase at least as the square of the diameter, small diameter ferrite rods should be used in high power applications. By the use of 0.15 inch diameter rods and a dielectric holder with good heat conductivity, rotator devices capable of handling up to 500 watts of CW power at X-band have been constructed.

Another method of solving the high power problem is to use thin hollow cylinders of ferrite. A typical cylinder at X-band might have an inside diameter of 0.75 inch and an outside diameter which is equal to the inside diameter of the brass waveguide, namely, 0.90 inch. The advantages of this structure are (1) the dissipative area is very large, (2) the loss per unit dissipative area can be made very small by reducing the thickness of the ferrite cylinder and (3) the direct contact between the ferrite and the brass waveguide allows the heat generated in the ferrite to be conducted away quite efficiently. An X-band rotator capable of handling over 1000 watts of CW power has been built using this technique.

As can be seen from the discussion in this section, the choice of ferrite material and rotator configuration is determined by the particular application. Some of the factors which govern the design are operating frequency, bandwidth, power handling capability, insertion loss, and physical size of the device. It is the job of the engineer to effect the best compromise among the factors which are of primary importance in his application.

MICROWAVE APPLICATIONS OF FERRITE ROTATORS

The microwave devices which make use of Faraday rotation can be broken up into two groups. The first group makes use of the non-reciprocal property of the ferrite rotation. The second group makes use of the relation between the rotation and the magnetization of the ferrite. That is, when the ferrite is operated below saturation, the rotation depends upon the applied magnetic field (see Figure 4).

The Rotator-type Gyrator

One of the first devices to utilize the non-reciprocal property of the ferrite rotation effect was the rotator-type microwave gyrator. A gyrator is a two-port device in which the phase shift through the device in one direction differs from the phase shift in the other direction by 180 degrees. This device consists simply of a 90 degree ferrite rotator section. In order to keep the input and output polarizations the same, a 90 degree waveguide twist is usually used in conjunction with the rotator section. Figure 9 shows an exploded view of a gyrator. The wave indicated by the solid arrows enters the waveguide twist and is rotated counterclockwise 90 degrees. With the ring magnet providing a longitudinal magnetic field, the ferrite rotates the wave clockwise 90 degrees.

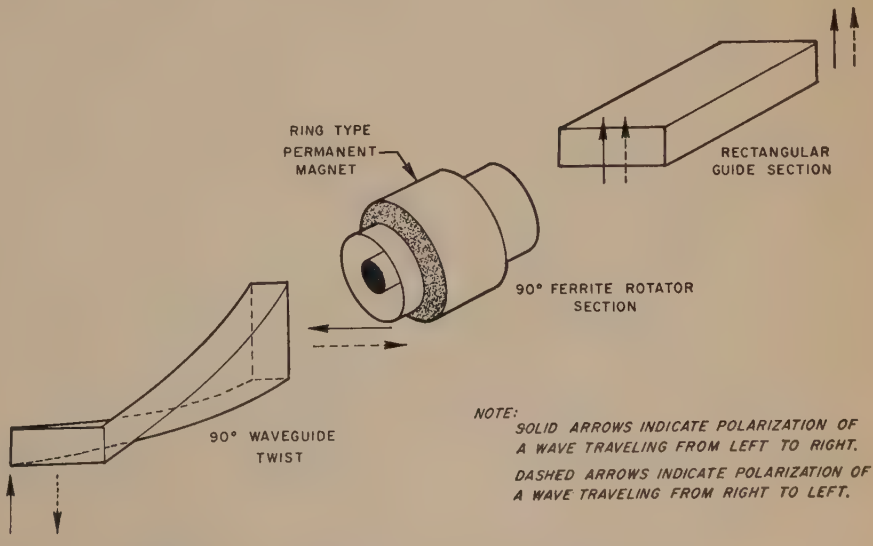

Figure 9 — An exploded view of a microwave gyrator.

Thus the wave appears at the output waveguide section with the same sense of polarization as it had at the input. If, however, a wave enters the rectangular guide section (dotted arrows) and propagates through the ferrite, the polarization will be rotated as shown in the figure. After passing through the waveguide twist, the wave becomes vertically polarized again. However, in this case, the *sense* of the vector has been reversed. That is the backward traveling wave (dotted arrows) experienced a 180 degree phase shift not experienced by the forward traveling wave (solid arrows).

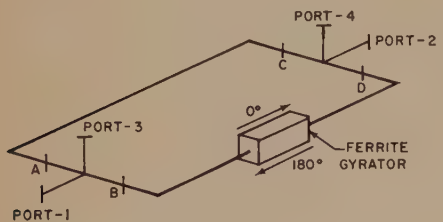

Figure 10 — A circulator employing a microwave gyrator.

The Gyrator-type Circulator

A very useful device which makes use of the gyrator's characteristic (viz., a 180 degree differential phase shift) is the circulator. This device shown in Figure 10, consists of two hybrid junctions and a ferrite gyrator. A wave entering port 1 splits between arms A and B. By proper adjustment of linelengths the two waves will arrive at C and D in phase and consequently will recombine in port 2. Energy entering at port 2 will split between arms C and D. The wave traveling through the gyrator will experience an extra 180 degrees phase shift and therefore the two signals will arrive at A and B 180 degrees out of phase. The action of the magic-tee causes all the energy to appear at port 3 and none at port 1. Similarly energy entering port 3 will proceed unattenuated to port 4 and energy entering port 4 will appear at port 1 unattenuated. One radar application of the circulator is as a duplexer in a transmit-receive system. If the transmitter is placed at port 1, the antenna at port 2, the receiver at port 3 and a matched load at port 4, all of the transmitter energy will be radiated by the antenna. Any signal received by the antenna will proceed to the receiver channel unattenuated. Reflections due to receiver mismatch will proceed to port 4 where it will be absorbed by the matched load. Since reflections at port 2 will appear at the receiver, it is important to keep the VSWR of the antenna very low in order to prevent receiver saturation.

The 45 Degree Rotator-type Circulator

Another method of obtaining circulator action is shown in Figure 11. This device employs a ferrite section with a saturation rotation of 45 degrees and a pair of two-mode transducers. Energy enters at port 1 vertically polarized and is rotated 45 degrees by the ferrite section. Since the output transducer is oriented at 45 degrees with respect to the input one, the energy from port 1 will appear at port 2 unattenuated. Energy entering at port 2 and passing through the ferrite section will be horizontally polarized and consequently appear at port 3. Similarly energy at port 3 will propagate to port 4 and energy at port 4 will propagate to port 1. Since this device is a circulator it can also be used in the duplexer application described above.

The Rotator Isolator

Another of many possible applications for this device is as a load isolator. In most radar systems there is a need for a device which allows the transmitter energy to propagate through it with negligible loss while preventing any of the reflected energy from appearing at the source. The load isolator is such a device. If matched loads are placed on both arms 3 and 4 of the circulator shown in Figure 11, the resulting unit is a load isolator. As noted earlier, energy from port 1 will propagate to port 2 with practically no loss. However, reflections from port 2 will be transmitted to port 3 where it will be absorbed. Thus since none of this energy appears at port 1, the VSWR seen by a microwave source attached at port 1 will be independent of the match of a component (antenna, mixer, filter, etc.) placed at port 2.

In practice, the amount of isolation that can be obtained with this type of isolator depends upon the ellipticity of the wave, the bandwidth of the rotator and the VSWR looking into ports 3 and 4. If the reflected wave arrives at the input transducer with some ellipticity, the vertical component will appear at port 1 and thus limit the isolation. Two causes of ellipticity are (1) lack of circular symmetry in the ferrite section and (2) difference in attenuation of the two counterrotating circularly polarized components of the linear wave. Typical performance figures at X-band are 30 db isolation with .5 db insertion loss over a 10% frequency band. For high power applications, one would use high power loads at ports 3 and 4. For low power use, the transducers can be replaced by sections of circular guide with resistance cards oriented at 45 degrees with respect to each other.*

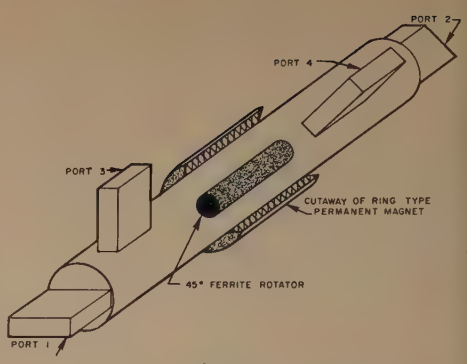

Figure 11
A 45 degree rotator type circulator.

An Electronically Controlled Microwave Switch

The second class of components employing the rotation effect make use of the fact that the polarization can be varied by means of an externally applied magnetic field. For example, if the ring magnet shown in Figure 11 is replaced by a solenoid and a current source, the device can be used as an electronically controllable microwave switch. With the current in the solenoid set up to provide the same magnetic field as the ring magnet, energy from port 1 will be transmitted to port 2. If the current in the coil is now reversed, the rotation will be reversed and the energy from port 1 will appear at port 4 with practcially none of it appearing at port 2. With a load placed at arm 4, an on-off microwave switch is obtained. The amount of isolation that can be obtained in the "off" position is usually from 20 to 40 db. In order to make the isolation insensitive to slight current variations, the ferrite should be operated at saturation. Thus a change in current will produce very little change in the polarization rotation.

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*See, for example, C. Bowness, "Microwave Ferrites and Their Applications," *Microwave Journal*, Vol. 1, No. 1, pp. 13-21.

A Ferrite Amplitude Modulator

Another use for the above structure is as an amplitude modulator.** With the ring magnet shown in Figure 11 replaced by a coil, sinusoidal amplitude modulation of the microwave energy can be obtained by the application of a sinusoidal current. When the current in the coil is zero, the polarization of the wave is not rotated by the ferrite and thus the energy splits equally between ports 2 and 4. Hence with a matched load on arm 4, the insertion loss from port 1 to port 2 is 3 db. If one now applies a current to the coil such that the rotation of the plane of polarization as seen looking from port 1 toward port 2 is clockwise, the amplitude of the signal at port 2 will increase. A reversal of the current direction will cause the wave to rotate counterclockwise and hence reduce the amplitude of the signal below the quiescent or 3 db value. For small rotation deviations (less than about 30 degrees) one can show that a sinusoidal current will produce a sinusoidal amplitude variation of the microwave signal. For large rotation angles the modulation becomes distorted. That is, second order sidebands appear at the output.

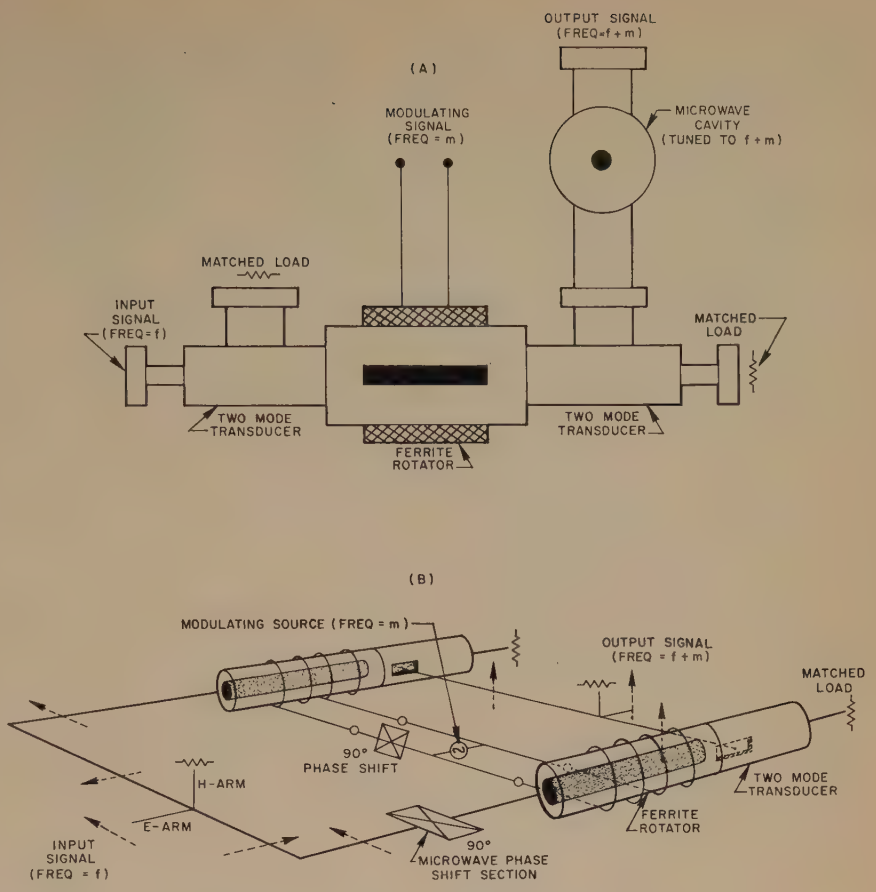


Figure 12 — Two types of single sideband generators.

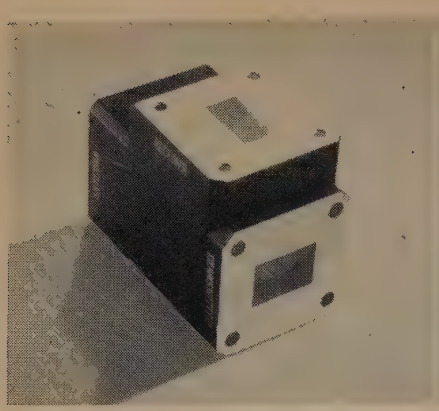
Ferrite Single Sideband Generators

Ferrite rotators can also be utilized in the design of single sideband generators. These are two port devices in which the input microwave signal appears at the output shifted in frequency. One method of accomplishing this is shown in Figure 12a. The input signal enters at the left vertically polarized. Upon passage through the ferrite section the polarization is varied at a frequency m. In the quiescent condition (zero rotation) all the energy is absorbed by the matched load on the right and none of the energy appears at the sidearm of the output two-mode transducer. A current in the coil in either direction will cause a rotation and hence the horizontal component of the rotated wave ($E_{in}\sin\theta$) will appear at the sidearm of the output transducer. Note that the amplitude of the microwave energy increase is independent of the direction of current and also that the polarization experiences a phase reversal as the current goes through zero. This signal is a carrier suppressed double sideband signal. That is, the signal appearing at the sidearm of the output transducer contains the frequencies f + m and f — m but not the carrier frequency f. If the modulating frequency is high enough (e.g., greater than 5 Mc at X-band), a cavity can be used to select one of the sidebands. The other sideband will be reflected and absorbed by the sidearm load of the input transducer. With a reasonable amount of modulating power (10 watts) a conversion efficiency (wanted sideband power per input power) of about — 10 db can be obtained at 5 Mc. It should be noted that in order to minimize the modulating power required, the rotation per ampere should be maximized. Therefore, unlike the load isolator application in which the ferrite is saturated, the modulator should employ a structure with the maximum amount of rotation that is consistent with loss requirements.

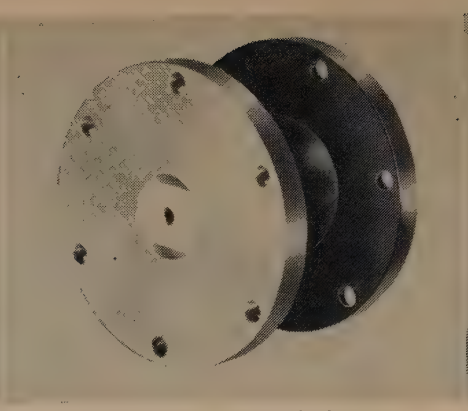
Due to the practical limitation on cavity selectivity, the above technique cannot be used with a low modulating frequency. A single sideband system that can operate at low as well as high modulating frequencies is shown in Figure 12b. The microwave energy enters the magic-tee at the left horizontally polarized and is split between the two coplanar arms. The signals enter a pair of rotators with one phase shifted by 90 degrees. A modulating current of frequency m is applied to the coils on the rotators and again one is phase shifted by 90 degrees. With zero current all the microwave energy is absorbed in the two matched loads on the output two-mode transducers and none appears at the sidearms. When a current is applied to the coils, the polarization vectors are modulated and carrier suppressed double sideband signals appear at the sidearms of the transducers. Now when the signals are recombined in the output magic-tee, one sideband (f-m) appears at the arm with the matched load and is absorbed. The other sideband (f + m) appears at the output port.

To show that the 90 degree phase shifts allow the two sidebands to be separated by the output magic-tee, a vector representation of the modulation process is shown in Figure 13. The large vectors represent the carrier signals entering each rotator, one of which has been phase shifted by 90 degrees. The small counterrotating vectors represent the upper and lower sidebands generated by the rotator.

**See Bowness, loc. cit.



A K_e-band medium Power Circulator



A C-band low Power Isolator

An X-band low Power Isolator

A group of typical microwave ferrite devices.

Since the two rotators are being modulated 90 degrees out of phase, the orientation of the sideband vectors with respect to their carrier should differ in the two cases by 90 degrees. As can be seen from the figure, this combination of phase shifts causes the upper sidebands to be in-phase and the lower sidebands to be out-of-phase. Thus all the upper sideband energy will appear at the sum arm of the magic-tee while the lower sideband will appear at the difference arm.

The Shorted Turn Problem

One of the major problems with the above device and, in fact, all ferrite modulators is the shorted turn problem. Since the rotator coil is wound on the metallic circular waveguide, the guide acts as a shorted secondary of a transformer. Hence it tends to shield the ferrite from the ac magnetic field generated by the primary coil. At high modulating frequencies this shielding is quite effective and methods of avoiding the shorted turn effect are necessary. One method is to evaporate a very thin metallic layer on the dielectric holder and have it act as the waveguide. If the layer is thin enough, the resistance of the secondary is increased and the shorted turn effect decreased. In practice the thickness of the layer must be less than 10^{-4} inch in order to be effective. Another method is to put a longitudinal slot in the waveguide. This reduces the shorted turn effect considerably but also leads to microwave leakage. This leakage can usually be reduced by an r-f choke arrangement or by covering the slot with a dielectric coated metallic strip which acts as an r-f bypass capacitor. By use of these techniques, conversion

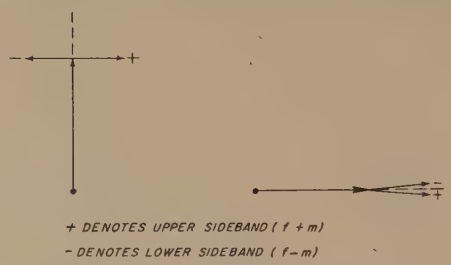


Figure 13 — Vectorial explanation of the sideband separation effected by two 90 degree phase shifts.

efficiencies of —16 db with 10 watts of modulating power have been obtained at as high as 30 Mc.

CONCLUSION

This paper has reviewed some of the microwave properties and applications of ferrite rotators. Microwave devices that utilize other properties of the ferrite have also been constructed. For a description of these devices and a comparison between these components and the rotation devices, the reader is referred to the article by Bowness in the first issue of the *Microwave Journal* (see footnote Page 32).

In conclusion, it should be noted that this paper contains but a few of the many applications that have been found for ferrite rotators. It is hoped that as more engineers become acquainted with the properties of ferrite rotators many more applications will be uncovered.

ACKNOWLEDGMENT

As is usual in a paper of this sort, the ideas described here are due to many workers. Although it is impossible to name them all, I have listed some of them and their contributions in the following bibliography:

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MICROWAVES

PART 2

E. L. GINZTON

We present the second part of Dr. Ginzton's article. We are indebted to the publishers of Science Magazine who gave us permission to present it to our readers.

Generation of High Frequencies

Despite many technical difficulties, electronic devices of more or less conventional design have been developed to permit practical application of microwaves at wavelengths as short as two or three millimeters. Outstanding examples of this work are the miniature magnetrons developed at Columbia University and the backward-wave traveling-wave tubes developed at the Bell Telephone Laboratories. Beyond these wavelengths, due to the fundamental limitations mentioned above, the conventional methods do not appear to be useful, even if the fabrication difficulties associated with small size could be resolved. Although as yet there are no obvious means for overcoming this limitation, there are several approaches to the problem now being pursued. It is too early to judge their possible success, but a description may serve as a good example of the work being done in this field.

In one approach, an attempt is being made to obtain microwave radiation from high-energy ("relativistic") electrons by subjecting them to periodic forces. Experiments which use relativistic electrons are currently being conducted by Motz at Oxford University, Coleman at the University of Illinois, and Mallory at Stanford University.

For the sake of illustration, consider an example of one such device, the "undulator" described by Motz and shown in Fig. 2. The electrons are emitted from a cathode (not shown in the illustration) and are accelerated to a velocity closely approaching that of light; this can be readily accomplished by the use of a microwave linear electron accelerator, the understanding of which is again not essential for the present purpose. In the undulator shown, the electrons are made to pass between the poles of the magnets, which are arranged as indicated in Fig. 2. The presence of the periodically spaced magnets causes the electrons to be deflected transversely and to undulate through the system. To understand the operation of this device, suppose an observer is located at some point along the axis of the electrons, as indicated in the illustration. An observer in this position, looking at the electrons head-on, would "observe" that the electrons are vibrating as if they were a current in a dipole antenna; he would, therefore, expect that the undulating electrons would radiate at a frequency which would be equal to the vibrational or undulational frequency of electrons. This frequency, he might think, is equal to the spacing of the magnets divided by the velocity of the electrons, which is approximately that of light. However, this expectation must be corrected because of two factors. Since the electrons are traveling virtually at the speed of light, relativistic effects must be taken into account, and this can be done by assuming that the spacing between the magnets is reduced. Thus, the electrons radiate at a frequency higher than would be expected if relativistic effects were neglected. Further, the electrons are moving toward the observer, and therefore the radiation from the electrons is Doppler-shifted. These two effects, taken together, result in radiation from the electrons (accelerated to a few million volts and with magnet spacing of a few centimeters) in the millimeter and submillimeter range. Experiments of this sort were first done by Motz, who used the linear electron accelerators available at Stanford University; these experiments have in fact shown that the principle can be used to produce electromagnetic radiation which completely bridges the gap between the radio region and the region of visible light.

The principal question that arises in examining the performance of the undulator is that of what intensity can be expected from it. Analysis shows that the behavior of the undulator is very strongly affected by the manner in which the electrons are injected. If the electrons can be sufficiently "bunched" by the linear accelerator prior to injection, so that the longitudinal length of a given bunch is approximately equal to the wavelength which one is interested in generating, the radiation process can become quite efficient. This is due to the fact that all the electrons in the bunch would radiate "together"—that is, radiation from each electron would reinforce radiation from the others. The practical problem is, therefore, to cause the electrons to bunch very tightly; this happens to be a difficult problem and is the central one of current research.

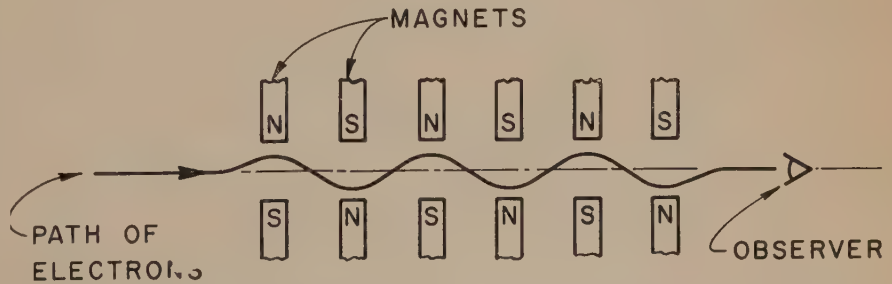

Figure 2 — Elements of the Motz undulator. Electrons arrive in bunches from the left, from a linear electron accelerator, and are forced to execute periodic vibrations due to the forces exerted by the magnets. The observer (with the aid of suitable detectors) at the right will find electromagnetic radiation of a higher frequency than the microwave frequency in the linear accelerator.

The undulator is not the only means for extracting power from the tightly bunched stream of relativistic electrons. Mallory, at Stanford, has observed that injection of a bunched electron stream into a hollow metallic tube produces radiation in the submillimeter range without the employment of any transverse undulation. This phenomenon, which is believed to be due to the extraction of higher harmonics from the bunched beam, seems to be related to the behavior of ordinary nonrelativistic frequency-multipliers. The success of devices other than the undulator also depends upon the initial degree of bunching which can be obtained.

The use of relativistic electrons cannot lead to development of simple, small, inexpensive sources of laboratory power, since this requires a powerful microwave source and a means for accelerating electrons into the relativistic region. Even so, the successful development of these devices would stimulate further experimentation and development and should eventually result in new approaches to the problem.

A different approach is currently being pursued by Linhart of the Comité Européen de Recherche Nucléaire (CERN) in Geneva. Linhart intends to use plasma phenomena in a novel way. His idea can be understood by considering a mechanical analog, as shown in Fig. 3. A weight is suspended from a string which passes over a support, and this can be adjusted to shorten the length of the pendulum or "oscillator." It is well known that the work done by the force *F* will cause the swinging pendulum to oscillate at an increased frequency, as the string is shortened, provided that the fractional decrease in the length of the string is small during a single cycle of oscillation. According to a well-known theorem, if this "adiabatic" criterion is obeyed, the internal energy of the oscillator will be proportional to its frequency. In principle, this can be applied to the microwave case in a manner shown in Fig. 4. Suppose a microwave cavity, which can be tuned by a moving plunger, is excited at some specific position of the tuning plunger by a source of microwave power until steady-state resonance conditions are established. If the power were then turned off suddenly, the fields in the cavity would attenuate exponentially with time. If, however, during a period of time which is short compared with the decay time, the plunger is moved rapidly downwards to reduce the volume of the cavity, then the work done on the cavity (as shown by analogy with the pendulum) will result in an increase of the frequency of oscillation and in the generation of electromagnetic energy. (As in the case of the pendulum, the reduction of the cavity volume must be adiabatic — that is, the change in length of the cavity must be small during a single cycle of oscillation.) It is easily demonstrated that the mechanical deformation of a microwave cavity by this process is completely out of the question because of the extreme velocities needed. However, Linhart suggests the use of a plasma phenomenon which seems to have the proper characteristics for the problem. He believes that a column of plasma (indicated graphically in Fig. 5), produced by ionization of some suitable gas by a second electron stream, can be excited as an electrical resonator and would have very low losses. (This suggestion is believed to be due originally to Fainberg of the U.S.S.R.) If the electrons of the plasma column are suddenly accelerated, the resulting electron current creates a magnetic field around the plasma which causes the electrons to converge radially, or to "pinch." During this pinch, the inward motion of the electrons produces the desired rapid decrease of size of the plasma resonator and should result in the phenomena described above in terms of the mechanical tuning of the cavity. Research along these lines is currently being pursued by Linhart and his associates.

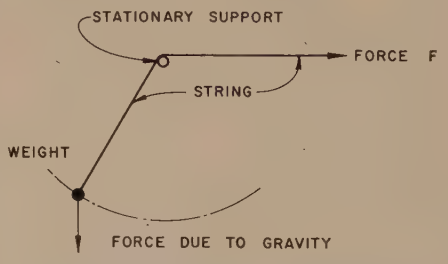

Figure 3 — A pendulum which, by shortening of its length, demonstrates the adiabatic principle of frequency multiplication.

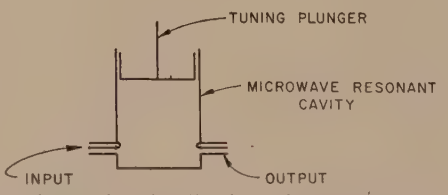

Figure 4 — Application of the pendulum principle to a microwave case; the motion of the tuning plunger compresses the stored energy and increases the frequency of oscillations.

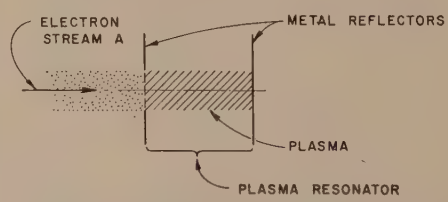

Figure 5 — The use of plasma as a microwave resonator.

Still other ideas which make use of plasma phenomena are being considered by workers in several countries; these are all speculative, since the characteristics of plasmas are still only partially understood.

Novel Methods of Amplification

In all conventional amplifying devices, including the triode, the klystron, the traveling-wave tube, and others, direct-current power is converted to radio-frequency power by first accelerating electrons from rest and then removing a part of the kinetic energy of the electron stream by exposing the electrons to radio-frequency fields in the output section of the amplifying device. Although this basic process can be executed in a number of useful ways, all of these have certain fundamental limitations, as previously mentioned. Two of the basic difficulties encountered with all electron devices are as follows: (i) Even in the absence of an input signal, all electronic devices produce an output, which is usually referred to as "noise." This is due to the fact that charged particles (that is, electrons) induce electrical signals in the output circuits due to random emission from the cathode and random variation in their velocity. (ii) Electrons even at the highest practical voltages have velocities which are not large enough to permit instantaneous interaction with radio-frequency fields; as in the triode, the "transit-time" effects preclude the extension of known techniques above a certain frequency limit.

Electronic devices of this sort are not, of course, the only means of generating electromagnetic energy. The generation of visible light is a familiar example of a process which is considerably different. In this case (to use the terminology of classical physics), electrons in one orbit can be transferred to a higher one by ex-

Table 1. Frequency and wavelength of electromagnetic radiation that can be expected from the various types of atomic, nuclear, and magnetic transitions.

Type of transition	Representative change in energy (electron volts)	Corresponding radiation	
		Frequency (Mcy/sec)	Wavelength (cm)
Atomic-electronic transitions (visible light)	~ 2	6×10^{8}	0.5×10^{-5} (5000 A)
Molecular transitions:			
Vibrational	10^{-3}	2.5×10^{5}	1.2×10^{-1}
Rotational	10^{-4} to 10^{-5}	2.5×10^{4} to 2.5×10^{3}	1.2 to 12
Paramagnetic ions (orientation of)	10^{-4} to 10^{-5}	2.5×10^{4} to 2.5×10^{3}	1.2 to 12
Nuclear moments (orientation of)	$\sim 10^{-7}$	25	1200

citation (as in gas discharge), and this will result in emission of light when the electron spontaneously returns to its original orbit. This process demonstrates the principle of conversion of energy (in a gas discharge, from a direct-current source) to electromagnetic form by the use of electrically neutral atoms. In terms of contemporary theories, it can be said that a neutral atom can radiate a quantum of energy in undergoing the transition from one allowable energy state (orbit) to another allowable state. It has recently been demonstrated that this principle can also be applied to both the generation and amplification of microwave power. Since this process does not use charged particles, but rather neutral atoms, it is possible to visualize devices which would have the same sources of noise and would considerably increase sensitivity in the detection of weak signals.

To understand the possible application of this principle to the generation and amplification of microwave frequencies, it is first necessary to consider the separation between energy states in molecular, atomic, and nuclear structures. According to quantum theory, the motions of electrons in atoms, of atoms in molecules, and of fundamental particles in nuclei are restricted in a manner which results in discrete energy-state levels (analogous to the classical concept of electron orbits in atoms). The excitation of an atom or a molecule can change its state from one level to another, and radiation of energy will take place upon return to the original state. According to the Einstein equation,

$$\triangle W = hv$$

where $\triangle W$ is the energy change, h is Planck's constant, and v is the frequency. If W is measured in electron volts, and v in megacycles per second, this relation becomes

$$\triangle W = 4.14 \times 10^{-9} v$$

Table 1 shows a few of the possible types of transitions together with typical values of energy changes which can be expected in such transitions. The last column in the table shows the frequency and wave-length of the radiation which results from such transitions. From this table it can be seen that rotational molecular transitions can be expected to generate radiation in the microwave range and vibrational types of transitions in the millimeter (and shorter) range.

That emission of radiation from a molecular system is possible does not, in fact, mean that this can be accomplished as simply as generating visible light by excitation of atoms in a gas discharge. To understand this, consider a molecule with two energy states between which transitions can occur. If the molecule is in the lower energy state, it can absorb microwave power and be raised to the high-energy state; if it is in the higher state, it can radiate the energy in the process of transition to the lower state. It turns out that the probability of these processes occurring is the same, and in a body of gas or other material with equal population densities of the two states, the radiation of energy is impossible. In the actual case, with common materials at thermal equilibrium, there is an excess of lower-state molecules, and the medium can only absorb radiation. This fact has been well known and it explains why molecular radiators have not been developed until a short time ago.

Recently, suggestions of Townes at Columbia University and of others have changed this picture. They have demonstrated that it is possible to separate the energy states to provide a region in space where an excess of molecules in the upper state, capable of emission of radiation, can be made to exist. A device of this type, called a "maser," may be of interest since it is the first and still the clearest demonstration of an important new principle. (The word *maser* has been derived from "*m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation.")

A schematic diagram of the principal elements of the Townes maser is shown in Fig. 6 (the walls of the vacuum chamber which surround the entire apparatus have been omitted). Although any one of a number of gases can be used, Townes selected ammonia for his experiments because the transition frequency occurs in a convenient microwave region, and because the population-density differ-

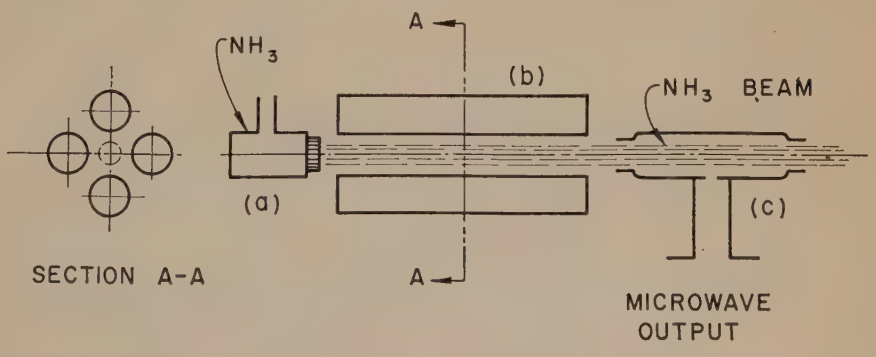

Figure 6 — Schematic diagram illustrating the principle elements of a device for generating or amplifying microwaves without the use of electron beams. (a) Shows the "source" of ammonia gas through which the gas diffuses through small tubes; (b) the "focusing elements" whose cross section is shown at the left; (c) the microwave cavity and the output waveguide.

ence in one pair of states happens to be particularly large. Ammonia gas at reduced pressure is introduced into a box, called the "source," from which it diffuses through an array of small tubes to form a molecular beam, as indicated in the diagram. The beam then passes between sets of rods, called the "focuser," in which alternate rods are connected together electrically, with a high electrical potential applied to the adjacent rods from a direct-current source. Although the focuser does not supply any electrical power to the system, it does two things: As the molecules drift between the rods, the presence of the electric field causes the molecules to become polarized in the form of electric dipoles and, as a result of this, causes many of the lower-state molecules to be defocused and removed from the system by outward radial drift. The beam which finally enters the last region of the maser, the microwave cavity, therefore contains an excess of molecules in the upper state and is in the proper condition to radiate this excess energy. If the number of upper-state molecules sufficiently exceeds the number of lower-state molecules, the radiation from the former can create a field in the resonant cavity which can be extracted for use by means of microwave waveguide, as shown in Fig. 6. The frequency of operation of the maser, as built by Townes, is 23,870 megacycles, and this can be shifted by only a small amount by tuning of the cavity or changing of the focusing voltage.

If the ammonia beam current is too low, the device will not oscillate. In this case, however, the maser can be used as an amplifier. Due to the presence of the ammonia current, the losses in the microwave cavity can be made to be negative, and a signal sent into the cavity can be reflected in amplified form. Since the ammonia amplifier does not employ charged electrical particles, there is no noise of the conventional sort induced in the microwave cavity. Recently, measurements by Helmer, at Varian Associates, have shown that the ammonia maser, when used as an amplifier, has only about twice the noise level expected from an "ideal" amplifier.

Although the ammonia maser is potentially very useful as an amplifier, and also as a source of extremely stable microwave frequency, it does have certain characteristics which limit its use in many important applications. The principal difficulties with the maser are as follows. The electrical bandwidth of the maser is very small — in the neighborhood of a few thousand cycles — which limits its application to those cases where the information is narrow-band. Amplification by the ammonia maser occurs at a fixed transition frequency, and the device cannot be "tuned" to other microwave frequencies (except, of course, to other discrete frequencies at which different molecular transitions are possible). Due to the limited current which can be obtained in a molecular beam, the power output of the maser is very low, in the neighborhood of 10^{-9} watt. In many applications of practical importance, one or more of these limitations represent a serious obstacle.

It appears, however, that there are other possible methods which might be used to separate energy states in a medium to create a situation conducive to transitions in the microwave region. For example, it is possible to expose certain solid materials to microwave radiation of one frequency to equalize the population densities of two energy states (one of which at room temperature has very low population density) and to induce a transition from one of these to a third energy level. This process, currently referred to as "pumping," can be accomplished by a number of methods and promises to provide many combinations suitable for application in the microwave region. A combination of such pumping methods, the splitting of energy levels by means of static magnetic fields, and the use of materials with suitable properties represents a field of research of great importance, from which amplifiers of near-maximum sensitivity might be expected to arise.

High Power and Large Bandwidths

Despite the fact that microwave devices have already proved capable of very high power generation over very broad bandwidths, there are still two kinds of reasons for trying to exceed the performance of the presently available devices. The first of these is a specific one: There are a number of immediate applications which can profitably employ higher power or larger bandwidths, or both. For example, in both radio communications and in radar the use of higher power permits communication over a greater distance and with greater reliability; in particle accelerators, higher power produces greater particle energies, and this, in turn, makes possible new experiments in high-energy physics. The second reason is a more general one: In working toward higher power, one finds various difficulties not previously encountered. The study of these difficulties sheds light on the ultimate limits which can be attained and yields information which is useful in improving the performance of devices which operate below the maximum power limits.

Large bandwidth is desirable for a variety of reasons, all related to the fact that it is becoming increasingly

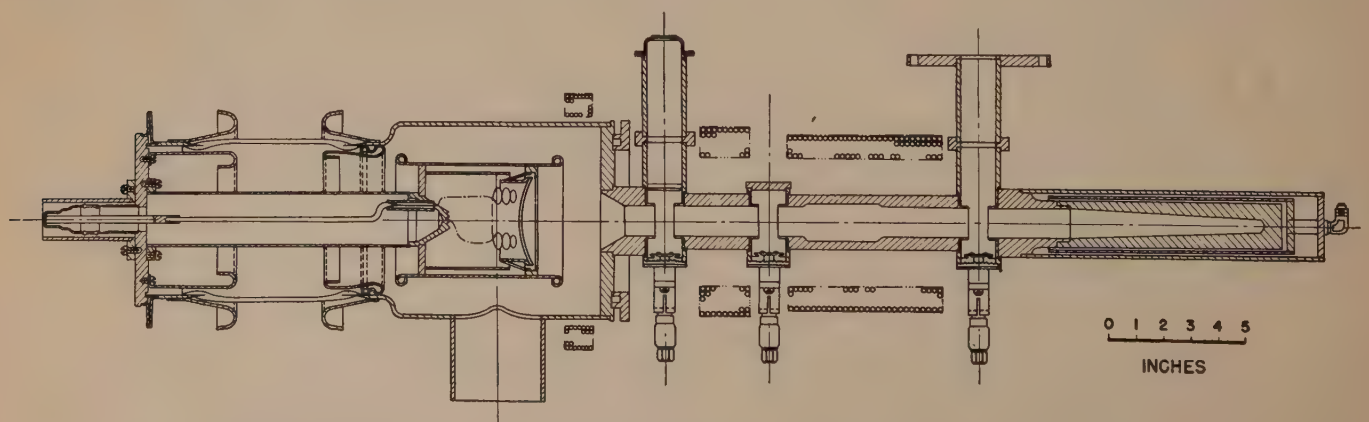

Figure 7 — A cross-sectional diagram of a high-power Stanford klystron. This tube, one of 22 used to power the Stanford "billion volt" linear accelerator, is capable of generating 30 million watts at a wavelength of 10 cm.

Figure 8—The high-power Stanford klystron illustrated schematically in Figure 7.

necessary to be able to transmit and to receive greater amounts of information in a given time. There are many reasons, too specific and detailed to be listed, which justify the search for greater intelligence-handling capability of both transmitting and receiving systems. In receiver work, extensive research carried out during the last ten years has resulted in design of a number of types of traveling-wave tubes which are either now available or are known to be possible. These tubes typically have bandwidths on the order of 30 to 50 percent, and nearly the whole microwave spectrum is covered by the series of tubes now available. However, in many applications it is not sufficient to be able to receive information over a large bandwidth, and the problem of generating power over a large bandwidth has many aspects which remain to be solved.

To illustrate the current research activity in these two areas, an example of each will be given below. These are representative of the efforts now being made in the laboratories in several nations.

High power. The highest peak power generated by a microwave tube to date is believed to be 30 million watts, produced at a wavelength of approximately ten centimeters by the klystron tubes which are used as sources of power for the Stanford billion-volt linear electron accelerator. A cross-sectional diagram and a photograph of this tube are shown in Figs. 7 and 8, respectively. In its principal features this klystron differs very little from the basic one shown earlier, in Fig. 1. To generate this power, the klystron used an accelerating potential between the cathode and the anode of approximately 360,000 volts, with an electron current of about 215 amperes. The power input to the klystron, therefore, approaches 80 million watts, not far from the electrical power used continuously by a medium-sized city. This power cannot, of course, be generated continuously but is obtained in pulses of a few microseconds' duration, repeated a few hundred or thousand times a minute. The power generated by the klystron is extracted by the last cavity and transmitted to the useful load by means of the waveguide shown through a ceramic or a glass "window," which isolates the vacuum in the klystron from the external atmosphere. In operating klystrons of this sort near their peak power limit, several difficulties are encountered. Some of these are described below. They represent several of the areas of major interest at the present time.

It is found that the "window" through which the microwave power passes often fails through being punctured (this spoils the vacuum inside the klystron). The processes in these punctures are not as yet clearly understood, although they seem to be related to the unavoidable irradiation the window receives from x-rays and electrons. The work thus involves an attempt to understand the exact mechanism of electrical failures of dielectric materials when subjected to irradiation, and also an attempt to solve the problem by finding materials with greater resistance to such radiation, or by finding practical methods of shielding the windows. A second problem in the operation of present tubes is electrical arcing in the anode-cathode region. Other work is concerned with study of cathode materials which might provide longer tube life and more reliable emission.

The research activity noted above involves, to a large degree, study of the characteristics of materials when subjected to unusual conditions: electrical stress at high frequencies, exposure to x-ray and gamma radiation, and so on. Progress in this field is necessarily slow since it requires the combined skills of chemists, physicists, metallurgists, and engineers, in addition to a long and expensive program of material research and testing.

A more specific microwave problem has to do with the efficiency of conversion of direct-current power to radio-frequency power in microwave tubes. Efficiency of operation becomes increasingly important as power levels increase, since power lost in heat becomes more expensive to consume and to supply. The basic design principles of klystrons, despite many years of experience, are not yet completely worked out because of the complex behavior of electron streams of high density when subjected to magnetic-focusing fields and radio-frequency forces. These complex questions are now being analyzed, with the assistance of large computing machines.

Large Bandwidth. As an example of the research being carried out to extend the bandwidth capability of high-power transmitting tubes, a high-power broad-band traveling-wave tube currently being developed at Stanford University is shown in Figs. 9 and 10. In its general configuration the traveling-wave tube resembles a klystron, having an electron stream which passes through a series of cavities. The main difference between the klystron and the traveling-wave tube is the following: The klystron uses a limited number of cavities, each one being simply a resonant circuit, and these are adjusted independently to respond to the frequency which one is trying to generate or amplify. The traveling-wave tube, of the type being discussed, has a number of cavities which are coupled together electrically to form a transmission circuit through which an electromagnetic wave can propagate from one end to the other. As the wave travels through the circuit it exposes the electrons in the beam to relatively weak electric forces, but for a protracted period of time. During this period of exposure, accumulated forces upon the electrons cause them to bunch and eventually to deliver power to the output terminals, much as with a klystron. Because a high degree of resonance is avoided by the use of tightly coupled electrical circuits, the electrical bandwidth of the traveling-wave tube can be many times that of a klystron.

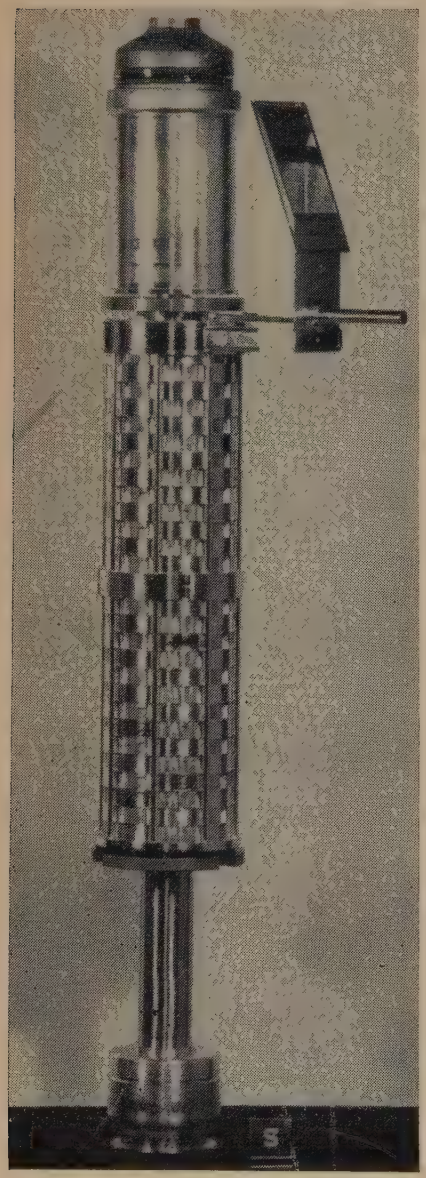

Figure 9—A photograph of a high-power broad-band tube. This device, representative of the current efforts to extend the bandwidth of microwave high-power tubes, is being tested by M. Chodorow and associates at Stanford University.

In order to make a satisfactory traveling-wave tube of the kind shown, it is necessary to design the assembly of cavities as if it were an electrical filter, and also to control the propagation velocity of the waves through the structure so that it will match the velocity of the electron stream. It is further necessary to arrange the fields in the cavities so that the electrons are exposed to the highest possible electric fields. These requirements cause the configuration of the cavity structures to become highly complex, so that understanding the behavior of such structures requires extensive experimental work and complicated analysis. Development of adequate theory for these kinds of microwave structures, experimental design of suitable cavity elements, and a great number of other practical problems still remain to be resolved before tubes of this class can be said to be fully understood and ready for practical application.

Conclusion

It is instructive to consider, in historical perspective, the way in which the microwave region of the electromagnetic spectrum came into use. During the 1930's, the "transit-time" of electrons, associated with conventional radio tubes, and the size requirements of circuit elements appeared to impose a fundamental limitation on the frequencies which could be used. This limitation was overcome by the development of resonant cavities and the formulation of the principle of velocity modulation. Thus, the microwave region was opened up, and with it came rapid development of new devices and new principles which have made possible important advances in communications, navigation, radar, particle accelerators, and a number of other fields which were not foreseen by the workers in the field. In like manner, extension of the usable electromagnetic spectrum into the millimeter and sub-millimeter region seemed, until recently, to be extremely difficult, if not impossible. With increased insight into such phenomena as molecular transitions, however, this limitation, too, appears now to be artificial. Work in this new field gives promise of developments which will also have great importance. The significance of this historical development seems sufficiently clear: the reservoir of knowledge fed by research almost inevitably flows over into new fields and new applications and provides methods by which still further knowledge may be acquired.

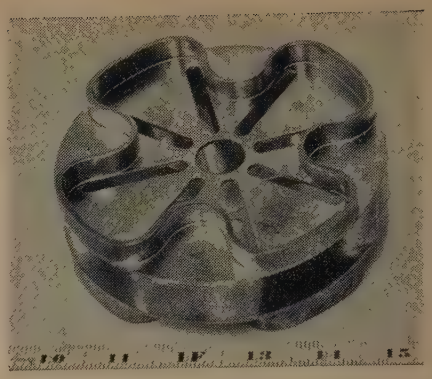

Figure 10 — A section of the "circuit" of the high-power broad-band tube shown in Figure 9.

The examples of current research listed in this paper cannot do justice, of course, to the intensive and varied research being pursued in many of the laboratories throughout the world. Not mentioned, for example, is the very important possibility of extending the findings of semiconductor research to the microwave region. Suggestions have already been made which may extend the present high-frequency limit of the conventional transistor and would permit the development of related devices at microwave frequencies.

It is my hope that the description of the accomplishments, applications, and current problems in this field of applied research is sufficient to demonstrate that the future of this work holds as much promise as it held for the pioneers of the microwave field in the mid-1930's.

Persons . . . . . Places

I-T-E NAMES GARRISON TO HEAD ENGINEERING PRODUCTS SALES

Paul A. Garrison has been appointed sales manager of the Engineering Products Section, Special Products Division, I-T-E Circuit Breaker Company, Philadelphia.

He will be responsible for sales of the Engineering Products Section, a major producer of radar antennas and systems and large waveguide for both military and commercial applications.

Garrison, 30, joined I-T-E in 1955 as sales representative for the Engineering Products Section. Prior to joining I-T-E, he was assistant to the president, Design Service Company, New York City.

Garrison was graduated with honors from the U. S. Naval Academy, receiving a bachelor's degree in electrical engineering. He completed a special course at Harvard Graduate School of Business Administration prior to taking his new position.

Garrison is married and has two children. He lives in Rosemont, Pa.

• • •

MICROWAVE ASSOCIATES STARTS NEW WING

Burlington, Mass., October 1, 1958. Microwave Associates, Inc. announces the start of construction of a new wing to its plant at Northwest Industrial Park at the junction of Routes 128 and 3 in Burlington, Mass. The new addition has been contracted to Vappi & Company of Cambridge, Mass. and upon its completion in March will provide additional space of approximately 18,000 square feet which added to the present plant completed in 1956 will total approximately 68,000 square feet. The new addition will provide expanded facilities for engineering and production of microwave tubes and semiconductors.

Power Sources, Inc., a company owned jointly by Microwave Associates, Inc. and Technical Operations, Inc., will consolidate all of its operations in a section of this new addition.

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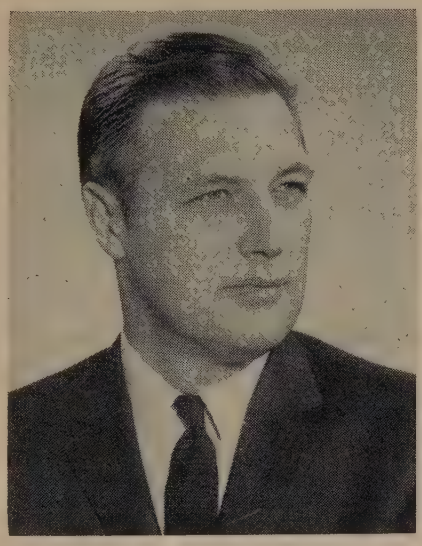

DR. OLIVER NAMED DIRECTOR-AT-LARGE.

Palo Alto, California — The national office of the Institute of Radio Engineers has just announced the appointment of Dr. Bernard M. Oliver as Director-at-Large. Dr. Oliver is Vice President, Research and Development for Hewlett-Packard Company in Palo Alto, California. Prior to coming to Hewlett-Packard, Dr. Oliver was with Bell Telephone Laboratories (New York) from 1940 to 1952. He received his Ph.D. degree in Electrical Engineering from the California Institute of Technology.

microwave engineers

• The Hughes Research and Development Laboratories are engaged in basic and applied research and development programs in a wide variety of fields, including antennas, radomes, microwave and storage tubes, masers, ferrite devices, microwave circuitry, instrumentation, and other fields.

One of the several interesting problems is the design of feedback loops for locking the local oscillator klystron to an available reference signal. The requirements – good stability and low noise in a very trying environment.

Your inquiry is invited.
Please write Mr. John Bailey.

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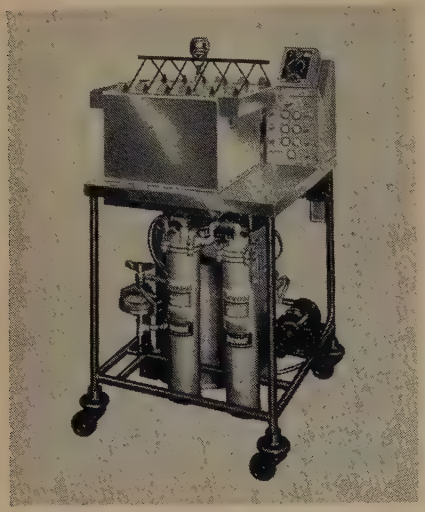
BARNSTEAD NEW TRANSISTOR WASHER

FOR WASHING and RINSING TRANSISTORS, DIODES, RECTIFIERS, TUBE PARTS and MATERIALS SUCH AS SILICON AND GERMANIUM



Maintains 15,000,000 OHM ultra-pure water while conserving make-up water through special re-purification cycle.

Best results with faster rinsing and fewer rejects are obtained when ultra-pure, hot water is employed in washing and rinsing of transistors, diodes, and other electronic components. The Barnstead Transistor Washer conserves thousands of gallons of water each day as it repurifies the pure, hot water keeping it free of organic impurities, and submicroscopic particles to 0.45 microns. Completely factory-assembled, ready for operation.

Partial Listing of Firms Using BARNSTEAD TRANSISTOR WASHERS

Clevite Transistor, Waltham, Mass.; Motorola, Inc., Phoenix, Arizona; Western Electric Co., Lauderdale, Pa.; Delco, Dayton, Ohio; Minneapolis-Honeywell, Brighton, Mass.; Bell Telephone Laboratories, Somerville, N. J.; Texas Instrument Co., Dallas, Texas and many others.

WRITE FOR CATALOG —

WATER STILLS, steam, gas and electric with capacities from ½ to 1000 g.p.h. **REGENERATIVE TYPE DEMINERALIZERS,** 50 to 2,500 or more g.p.h. **SUBMICRON FILTERS,** 400 or more g.p.h. Submicroscopic filtration to 0.45 microns

TRADE MARK REG U.S. PAT OFF

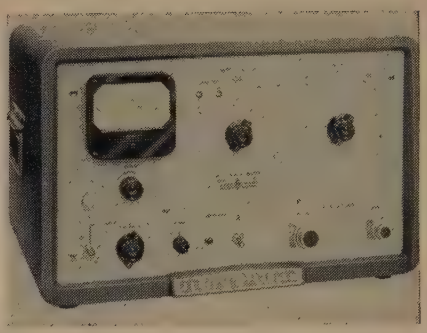
Barnstead
STILL & STERILIZER CO. Inc.

BOSTON JAmaica 4-3100	NEW YORK Kingsbridge 8-1557	CLEVELAND ACademy 6-6622
CHICAGO MUlberry 5-8180	PHILADELPHIA LOcust 8-1796	LOS ANGELES RYan 1-6663
JOHNSON CITY 3113	SAN FRANCISCO TEmplebar 2-5391	CHATTANOOGA 6-5863

48 Lanesville Terrace, Boston 31, Mass.

FIRST IN PURE WATER SINCE 1878

New Products



NEW METER FOR AUTOMATIC NOISE FIGURE MEASUREMENTS

A new noise figure meter which automatically measures the noise figure of amplifier and microwave receiver systems is now available from the Hewlett-Packard Company.

The instrument, Model 340A Noise Figure Meter, enables semi-skilled personnel to make quick and accurate noise measurements and to adjust receivers and components for optimum performance. Receiver performance can be improved with the 340A over the best adjustment previously pos sible.

Model 340A provides direct noise figure readings in db, needs no periodic calibration and operates over any frequency range for which there are noise sources. Receiver ranges from 2.6 to 18.0 KMC are covered with Hewlett-Packard's Model 347A Waveguide Noise Source. For IF amplifier measurement, the company provides Model 345A IF Noise Source operating at either 30 or 60 MC.

With the IF noise source, the instrument reads noise figure from 0 to 15 db with an accuracy of ± ½ db. With the waveguide noise source, it reads from 10 to 25 db with an accuracy of ± ½db, and from 3 to 30 db with an accuracy of ± 1 db.

In addition to its usefulness in optimizing receiver performance, Model 340A is particularly helpful in designing circuit components such as IF amplifiers, crystal mixing circuits and traveling-wave tubes.

CIRCLE READER SERVICE CARD 101

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DIPLEXING ASSEMBLY MAKES BOW

Microwave Relay Unit Combining 2 Fixed-Tuned Filters Is Offered By Airtron, Inc.

Signals of two different frequencies can be transmitted or received through

a common antenna with a microwave relay diplexing filter assembly developed by Airtron, Inc.

The unit is composed of two fixed-tuned filters (at different frequencies) mounted on the symmetrical arms of a compensated waveguide tee. Each filter has five stages, and can be fixed-tuned to any frequency within the 5925 to 6425 mc/s band.

A maximally flat (Butterworth) response is obtained with less than 1.0 db insertion loss when the bandwidth is 25 mc/s or more. Off-band rejection is at least 55 db at Fo ± 50 mc/s, and VSWR for the whole assembly does not exceed 1.20 within its pass bands.

This new diplexing assembly is the latest addition to Airtron's extensive line of microwave relay products including ferrite isolators, duplexers, waveguide switches and Flexaguide[R], along with bends, straight sections and 90° twists in aluminum and oxygen-free, high-conductivity copper.

CIRCLE READER SERVICE CARD 102

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SYLVANIA ANNOUNCES THREE NEW Ka-BAND MAGNETRONS

Especially Designed for Missile Radar Applications

New York — Three new Ka-band magnetrons especially ruggedized for missile applications have been announced by Sylvania Electric Products Inc.

The new tubes bring to a total of five the number of magnetrons for Ka-band (33-36 kilomegacycles frequency) applications available from Sylvania. The new types — M4063, M4064 and M4155 — plus the earlier 5789 and 6799, cover a power range from 20 to 100 kilowatts.

These tubes, which were developed at Sylvania's Special Tube Operations plant in Williamsport, Pa., are used for radar equipment where very high resolution is required. As the source of the pulsed outgoing signal, they are the "heart" of a radar set. Typical applications of the new tubes are in cloud-finding, mapping, and missile guidance equipment.

In addition to their ruggedness, the relatively light weight of the new tubes makes them particularly well-

suited to airborne applications. The 20-kilowatt M4063 weighs only nine pounds, while the 70-kilowatt type M4064 weighs 13 pounds. Between these is the 11-pound M4155, a ruggedized version of the 5789, which has a rated peak output power of 40 kilowatts.

In addition to these Ka-band magnetrons, Sylvania also manufactures other types for K-band applications such as airport traffic control and special missile uses, for X-band applications such as marine and airline radar and navigational and fire control radar, and carries on advanced development of new backward-wave magnetrons in the L, S, and X-band frequencies which are used for electronic countermeasures.

Other products of the division include traveling wave tubes, klystrons, ferrite isolators, and ferrite circulators, all operating in the microwave region, in addition to special purpose types such as decade counter tubes and triggers.

CIRCLE READER SERVICE CARD 103

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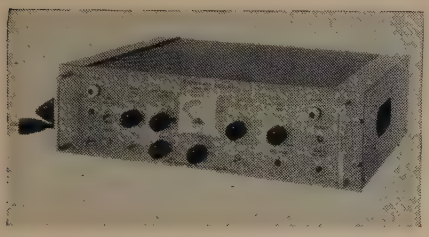

MICROWAVE LEVELER 703

Alfred Microwave Leveler Model 703 flattens RF power to ± 1 db from 2 to 4 kmc from backward wave oscillators, klystrons, signal generators, and traveling wave tube amplifiers. The instrument is specifically created for increasing versatility of voltage tuned microwave oscillators to permit measurements which require constant output at fast or slow electronic sweeps.

Microwave Levelers include a directional coupler for RF power sampling, a crystal detector, and a stable high gain amplifier. The signal level is compared with a reference voltage, amplified and brought out as a control voltage. The well regulated reference voltage and the chopper stabilized amplifier make the Leveler an ideal tool for maintaining constant power output with long term stability. The Leveler may also be used as attenuator to provide variable attenuation over the dynamic range of the associated control device. Typically, power output may be held to ± .1 db with 30 db input change at fixed frequency with devices having control sensitivity of .5 db volt or greater.

Control voltage is available either relative to ground for operation of low voltage control electrodes or full floating with 5 kv insulation for connection to control electrodes operating at DC high potential.

Other units are available in the 1 to 2, 4 to 8, and the 8 to 12.4 kmc frequency range. Models are available for maximum power ranges of 1 to 100 mw or 10 mw to 1 watt.

CIRCLE READER SERVICE CARD 104

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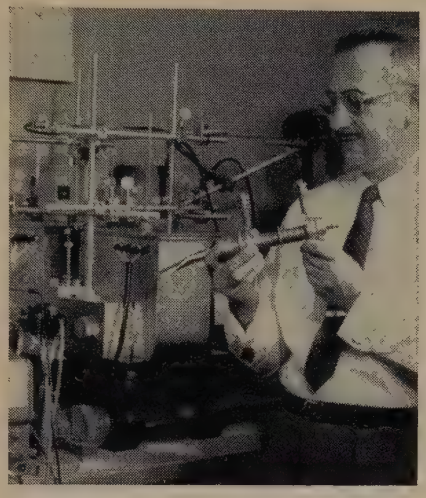

NEW SEMICONDUCTOR DEVICES DESCRIBED AT ELECTRON DEVICES MEETING

Several new semiconductor devices developed at Bell Telephone Laboratories were described at the Annual Meeting of the IRE Professional Group on Electron Devices which was held in Washington, D.C. Included was a family of high frequency diffused germanium transistors.

HIGH FREQUENCY DIFFUSED TRANSISTORS

Mr. N. C. Vanderwal discussed the design and development of small diffused germanium transistors as millimicrosecond switches and 100-500 mc oscillators and amplifiers. Objectives of the development program are transistors having high gain at high frequencies, reliability, low cost, and small size.

Mr. Vanderwal reported on some of the workable fabrication techniques, such as collector bonding and encapsulation designs, which have shown promise. He also presented some reliability evaluation results.

RADAR SYSTEMS AND COMPONENTS ENGINEERS

At Autonetics our current long-range programs and new programs require the addition to our technical staff of several unusually capable engineers having analytical, experimental, or developmental experience in radar microwave and antenna fields. Among our projects are monopulse radars for armament control and bombing navigation systems. This work ranges from basic research and analysis—leading to a choice of system parameters—to actual development of components.

The above positions are open to Engineers with B.S. engineering degrees, as well as to those who have graduate training. Salaries are competitive and open.

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A Division of
North American Aviation, Inc.

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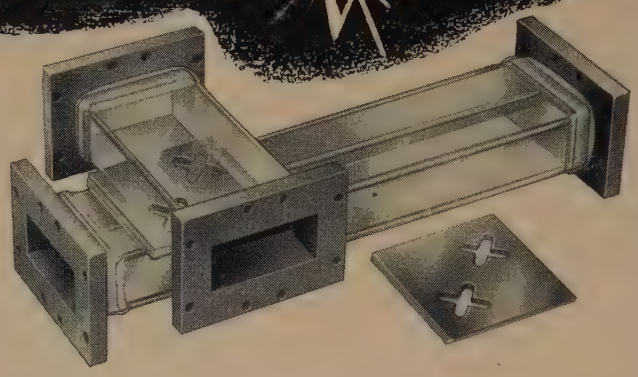

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This unique electroforming process produces precision, internally-shaped parts, such as this microwave coupler, with internal accuracies and configurations unobtainable or economically prohibitive with any other method.
The intricate interior is formed from the inside out, and may include machined parts that are grown in place during electroforming to produce an integral assembly of unusual accuracy, rigidity, and lightness.
Machined flanges are also grown in exact position to eliminate heat distortion associated with fabrication methods.
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CIRCLE READER SERVICE CARD 14

SYMPOSIUM ON MILLIMETER WAVES

Millimeter Waves will be the subject of the ninth international symposium of the Polytechnic Institute of Brooklyn, Microwave Research Institute, to be held in New York City on March 31, April 1, 2, 1959, under the co-sponsorship of the Air Force Office of Scientific Research, U.S. Army Signal Research and Development Laboratory, Office of Naval Research, and the Institute of Radio Engineers. The symposium is intended to highlight the present state of research in, and applications of, millimeter wave technology. Accordingly, the program will be devoted to invited and contributed papers treating the generation, transmission, control, measurement, and detection of millimeter wave energy. In addition, source material and significant advances in basic supporting fields will be summarized in tutorial papers chosen from appropriate fields in physics and engineering. A more detailed indication of topics which fall within the scope of the symposium is given below.

Interaction of millimeter waves and materials

Hall effect circuits, circuits utilizing ferromagnetic and paramagnetic resonances, cryogenic circuits, ferrite devices, equivalent circuit representations for active and anisotropic structures.

Solid state active millimeter circuits

Maser and parametric amplifiers and oscillators, solid state mixers and frequency multipliers, duplexing and switching circuits, active matching elements, discontinuities in active systems.

Millimeter electron tubes

Oscillators and amplifiers such as klystrons, magnetrons, backward wave oscillators, etc., Cerenkov millimeter sources, relativistic electron beam harmonic generators and radiators, millimeter-wave interaction with plasmas.

Radiating circuits and antennas

Antennas for millimeter waves, equivalent circuits for radiating discontinuities, radio astronomy.

Coupled line, multimode, and non-conventional transmission systems

Periodic structures in multimode waveguide, anisotropic media, surface waveguides, quasi-optic techniques, equivalent circuits for discontinuities in multimode or non-conventional waveguides.

Millimeter components

Filters, transformers, directional couplers, rotary joints, quasi-optic component techniques.

Millimeter circuit measurement techniques

New measurement methods, measurement techniques for non-reciprocal and active circuits, diagnostic measurements of plasmas with millimeter waves.

The closing date for submission of papers and/or 100 word abstracts is January 30, 1959. All correspondence should be addressed to:

Professor Herbert J. Carlin
Microwave Research Institute
55 Johnson Street
Brooklyn 1, New York

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NEW ANDREW ANTENNA SYSTEMS CATALOG

ANDREW Catalog 22, a 96-page product and facility book, will be a welcome addition to the reference library of antenna system planners and engineers. It fully covers the antennas, antenna systems, and transmission line products of this twenty-two year old concern.

Included in the ANDREW catalog are new product developments in 21-inch waveguide, high power transmission lines, ground-to-air and telemetry antennas, microwave and two-way communication antennas, and the introduction of two new sizes of HELIAX (flexible coaxial line).

In addition to complete engineering data on ANDREW products, the catalog includes a special 16-page section of general antenna systems engineering information.

The catalog is available on request by addressing ANDREW Corporation, 363 East 75th Street, Chicago 19, Illinois, on your letterhead.

CIRCLE READER SERVICE CARD 105

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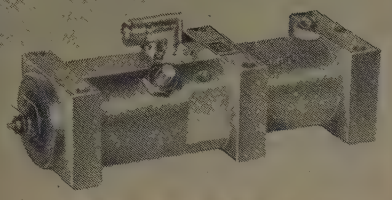
STRAND LABS

The Strand Labs, Inc., 217 California Street, Newton, Mass., has just released new descriptive data sheets on the Models 600 and 601 Microwave Electron-Paramagnetic Resonance Spectrometers and the Model 300 and Model 500 X-band Stabilized Microwave Signal Generators.

CIRCLE READER SERVICE CARD 106

NEW



AVION

"S" - BAND

pulse oscillator

model no. 306

- *offering superior stability for both vibration and temperature under extreme environmental conditions . . .*
- *small-size and light-weight*

TUNING RANGE 300 MC (Nominal)

POWER OUTPUT 1.5 KW peak minimum at .001 duty cycle, 1 μsec pulsewidth, 1000 pps

TUBE GE 6442 triode

OPERATING CONDITIONS 3000 V at 2.5 amp peak (Nominal) Heater 6.3 V ac or dc (5%)

VIBRATION 20 g . . . 20-2000 cps (FM 2 MC max.)

SHOCK 70 g while operating (frequency shift 1 MC max.)

Temperature –50 C to 100 C (4 MC max.)

FIXED CATHODE Plate tuned (only tuning adjustment)

TUNING LOCKING DEVICE Output connector (type N, TNC, or BNC, nominally 50 ohms)

OVERALL DIMENSIONS Length 6-1/4"; Width 2"; Height 1-7/8" excluding connector

WEIGHT 20 oz.

MOUNTINGS Integral parts of the oscillator — included in the dimensions and weight, above

OTHER MICROWAVE COMPONENTS S, C, and X — bands available.

SEND FOR LITERATURE

AVION ACF AVION DIVISION

ACF INDUSTRIES

11 Park Place, Paramus, N. J.

CIRCLE READER SERVICE CARD 21

Manufacturer of COAXIAL ATTENUATORS Since 1947

Many standard models covering DC—10 KMC available using our own Metal Film and Cracked Carbon Film Resistors. Connectors: "N", "BNC", "C" and "7/8".

MODEL 10 Bilateral			MODEL 11 or 12		
Cat. No.	Nominal Attenuation D B	Power Sensitivity D B at 10 Watts	Cat. No.	Nominal Attenuation D B	Power Sensitivity D B at 10 Watts
10-1	1	0.01	11 or 12-4	4	0.02
10-2	2	0.01	11 or 12-5	5	0.03
10-3	3	0.01	11 or 12-6	6	0.03
.....	.....	.....	11 or 12-7	7	0.05
.....	.....	.....	11 or 12-8	8	0.07
.....	.....	.....	11 or 12-9	9	0.09
.....	.....	.....	11 or 12-10	10	0.10

WEINSCHEL

PRECISION 10 WATT POWER PADS

50 OHM IMPEDANCE

DC to 1 KMC FREQUENCY RANGE

1 to 10 DB ATTENUATION

Connectors: "N"
Model 10: bilateral.
Model 11: female input.
Model 12: male input.

- **Maximum Input VSWR. 1.15.**
- **Resistors: Artificially aged.**
- **Maximum Deviation of Insertion Loss from Nominal: ±0.2 DB (includes frequency sensitivity and DC inaccuracy).**
- **Calibration Frequencies: DC; 400 MC; 750 MC; 1000 MC.**

Weinschel Engineering

10503 Metropolitan Ave., Kensington, Md.

CIRCLE READER SERVICE CARD 22

FOUL-WEATHER-PIERCING RADAR USING CIRCULAR POLARIZATION DESCRIBED IN I-T-E BULLETIN

The first commercially available circular polarization feed systems for airport radars — making them capable of "seeing through" foul weather — are discussed in a new bulletin published by Special Products Division of I-T-E Circuit Breaker Company, Philadelphia.

The four-page bulletin — third in a series of reports on antenna system and waveguide engineering accomplishments — describes the innovations developed in producing circular polarization systems for the Civil Aeronautics Authority's ASR-2 and -3 and the Air Force's AN/CPN-18 airport surveillance radar systems.

Circular polarization radars provide a vast improvement in detection of aircraft during foul weather by significantly reducing the echo from rain, snow, clouds and dust which would appear on the screens of conventional radars.

In circular polarization, the fields of the radar energy are rotated to give a constantly changing polarization which produces an elliptical wave front that passes through bad weather unreflected.

Working from a laboratory prototype developed by Airborne Instruments Laboratory, I-T-E engineered reliable circular polarization systems which are now being added to the CAA and Air Force systems under a complete modernization program.

For these systems, I-T-E developed:

— A phase shifter that can handle as high as two megawatts of power while providing accurate phase shift over a wide band.

— A reliable polarization twister using an entirely new type of motor drive which has a guaranteed 5000-hour life between overhauls.

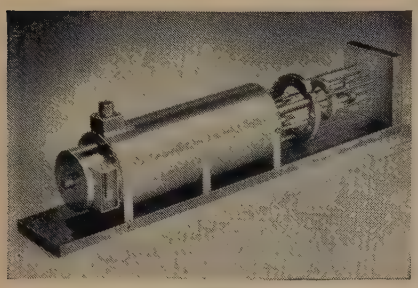
— A new antenna feed horn which gives accurate (plus or minus three degrees) relative phase tracking.

In order to evaluate the components it developed, I-T-E built a versatile testing range which permits circular polarization measurements to plus or minus one-tenth of a decibel of ellipticity.

CIRCLE READER SERVICE CARD 112

PROBLEM

Reduce costs in high powered TACAN systems



SOLUTION

J-V-M Tetrode Cavity

Here is a typical example of J-V-M Microwave Company's ability to coordinate its engineering experience and facilities with those of equipment, component and tube manufacturers. This L-Band tetrode cavity is considerably less expensive than the klystron which it is designed to replace. The cavity is for operation in the 900 to 1250 megacycle range. It employs the latest advancement in high powered tetrodes.

Many other tube-cavity combinations, including airborne, and a wide variety of other microwave components...antennas...wave guide adapters...mixers...multipliers...duplexers...etc....can be supplied to your specifications. We have complete design, engineering, manufacturing and testing facilities. Our expert microwave engineers will work in close coordination with you from blueprint to actual installation.

Tell us about your requirements. Ask for information and/or quotations on any microwave component. Let us prove that we can give you complete satisfaction—and save you time, money and manpower. Request catalog on our full line of standard items.

J-V-M

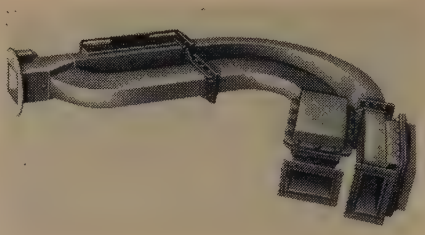
J-V-M MICROWAVE COMPANY

9311 W. 47TH ST. • BROOKFIELD, ILL.
Phone: HUnter 5-2000 TWX: Brookfield, Ill. 27966

ENGINEERS AND BUILDERS OF ALL TYPES OF MICROWAVE COMPONENTS

CIRCLE READER SERVICE CARD 17

NEW PRODUCTS



DUAL FEED HORN PROVIDES SAME CENTER OF RADIATION

A dual polarized feed horn for large size waveguide having two waveguide inputs has just been developed and put into use. The unique feature of this primary feed is the waveguide input, since the usual dual polarized horn requires a coax input.

The new feature has the advantage of providing the same center of radiation for both signals. Maximum power transmission is obtained in both polarizations. The horn handles 10 kw with more than 30 db decoupling between the signals.

The horn has been produced in the frequencies of 1700-2400 mc, 755-985 mc and 400-450 mc, but the design is available in other frequencies. For further information contact D. S. Kennedy & Co., Cohasset, Mass.

CIRCLE READER SERVICE CARD 106

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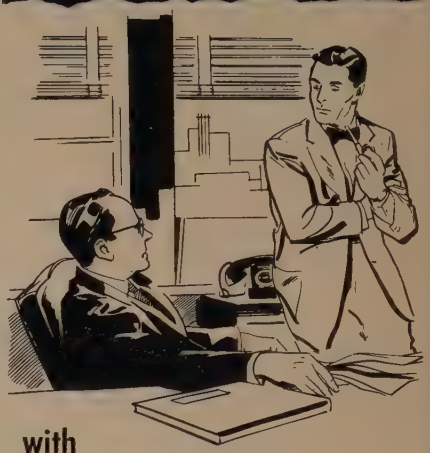
LFE CONDUCTS MASER RESEARCH

Research on 3 level solid state Masers is being conducted by Laboratory for Electronics, Inc., 75 Pitts Street, Boston, Massachusetts. Mr. Vance Holdam, Vice-President in Charge of Operations for the firm, stated that the material used is potassium cobalticyanide and that work is being done in S-band at 2800 Mc/s under the direction of Mr. Saul Bergman, of the LFE Applied Physics Group.

Mr. Holdam said that so far effort has been concentrated on a cavity type Maser, which has been successfully operated. He added, however, some preliminary studies were being made for Traveling Wave Maser development and that the company is planning to carry out additional research along that line in the future. Mr. Holdam said that the company is also studying parametric amplifier techniques.

CIRCLE READER SERVICE CARD 107

HAVING PROBLEMS ?



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CUSTOM COMPONENTS Inc. is the largest and most diversified Manufacturer of RADIO CORES & MICROWAVE COMPONENTS stressing "Quality, Economy and Service."

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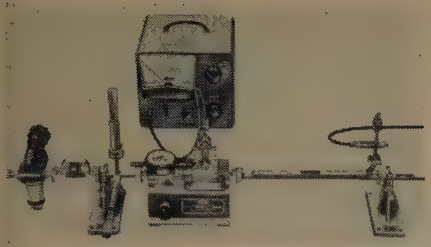
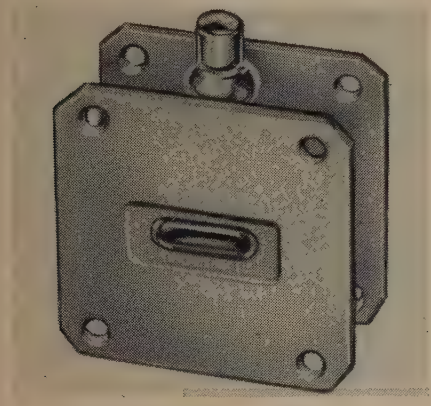


COMPLETE LINE OF MILLIMETER PRODUCTS INTRODUCED BY NARDA MICROWAVE

Specific equipment in K, V, Q, M, and E Bands which is now available includes Variable Waveguide Attenuators, Tuneable Waveguide Detectors, High Directivity Directional Couplers, Impedance Meters, VSWR Amplifiers, Terminations, E-H Tuners, Frequency Meters, and Waveguide Clamps and Stands.

The new equipment is extremely versatile for many types of microwave measurements, due to the precision and accuracy which go into its manufacture. Particular care is taken in each step of the fabrication to assure the additional precision required for the higher frequency ranges encountered. For example, silver or tellurium copper is used as waveguide material to maintain transmission losses at a minimum. Similar precautions are taken with all other millimeter components to insure their complete reliability.

CIRCLE READER SERVICE CARD 108



MINIATURIZED CRYSTAL PROTECTORS

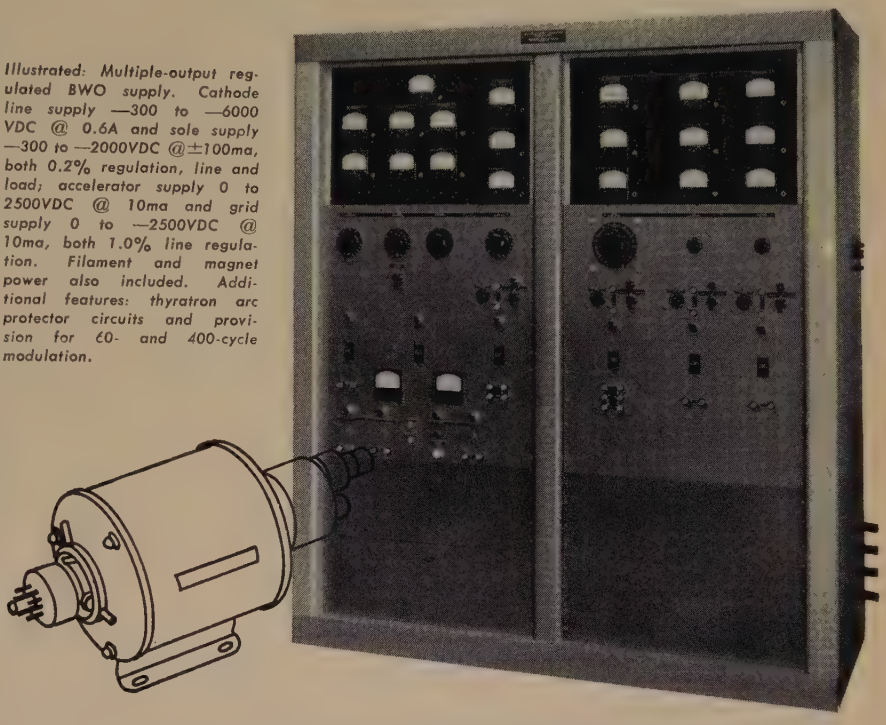
Bomac Laboratories, Inc., Beverly, Mass., announce a new line of miniaturized crystal protectors that are one-half the size of previous types. For example, the x-band tube is approximately ¾" between flange faces. The electrical characteristics are equal or better than the usual broadband TR tube, and they are available for all microwave bands.

CIRCLE READER SERVICE CARD 109

Testing MAGNETRONS KLYSTRONS CARCINOTRONS

● OTHER MICROWAVE TUBES, COMPONENTS OR SYSTEMS?

Illustrated: Multiple-output regulated BWO supply. Cathode line supply —300 to —6000 VDC @ 0.6A and sole supply —300 to —2000VDC @±100ma, both 0.2% regulation, line and load; accelerator supply 0 to 2500VDC @ 10ma and grid supply 0 to —2500VDC @ 10ma, both 1.0% line regulation. Filament and magnet power also included. Additional features: thyratron arc protector circuits and provision for 60- and 400-cycle modulation.



Come to Manson for the widest selection of standard *Pulse Modulators* and *High-Voltage Power Supplies* covering all useful power levels. From kilowatts to tens of megawatts, Manson has precision-engineered designs for operation and test of magnetrons, klystrons, traveling wave tubes, backward wave oscillators, lighthouse tubes, pulse transformers, waveguide components and related devices. The wide range of standard models is readily adaptable to meet individual specifications.

HIGH POWER PULSE MODULATORS:

Hard- and soft-tube types from 16 kw. to 30 megawatts peak power output, and higher. Average output powers as high as 60 kilowatts. Typical operating features include: continuously adjustable voltage control; discrete or variable pulse widths; internally- and externally-controllable repetition frequencies; auxiliary synchronized outputs; pulse-shape monitoring circuits; and interlocking and overload protection.

HIGH VOLTAGE POWER SUPPLIES:

High-voltage DC and AC types, single- or multiple-output, regulations and stabilities to 0.01%. Standard and custom designs to satisfy your specific tube testing or production problems: highly-regulated supplies uniquely suited for TWT test and operation; unregulated high-power supplies for systems testing; and complete power sources for controlling all aspects of tube production.

Write today for complete details on our full line of high-power pulse-test equipment and high-voltage power supplies, including applications and performance data.

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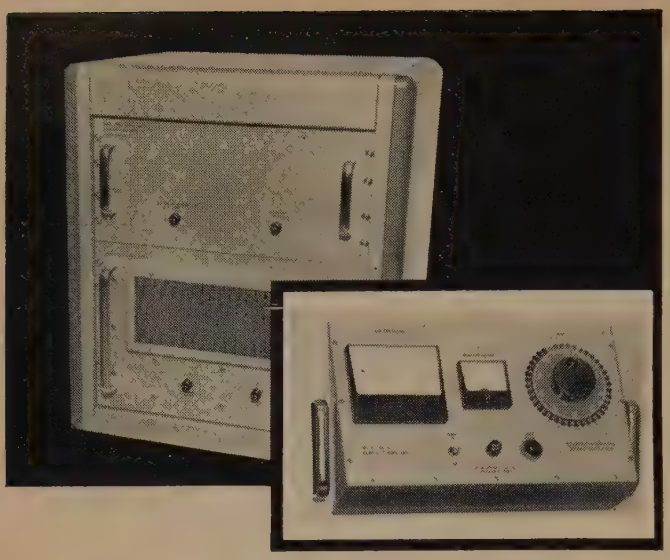

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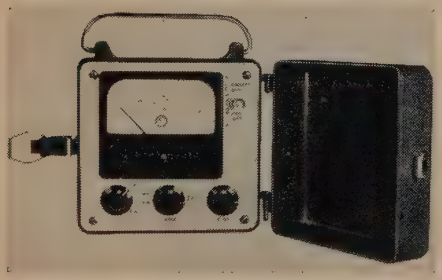


AIRBORNE INSTRUMENTS LABS TRANSISTORIZED PRECISION POWER BRIDGE

AIL's Transistorized Precision Power Bridge makes it possible to obtain fast, accurate and direct readings of microwave measurements. The instrument is compact, light in weight (can be held in the hand), and battery operated so that its complete portability makes it available for laboratory and field use.

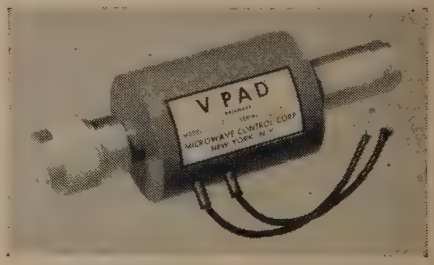
Description

The AIL Type 50 Transistorized Precision Power Bridge is a self-balancing device which permits direct reading of RF power in watts and dbm.

The Type 50 consists basically of an audio oscillator and a bridge in a closed-loop circuit. The amplitude of the audio signal is variable and is dependent upon and controlled by the condition of balance of the bridge. The balance of the bridge is in turn dependent upon the total power in the thermistor which, through the action of the closed loop, is maintained at a constant value. The audio power is therefore at a maximum value consistent with maintaining the bridge in balance. As RF power is applied to the thermistor, the bridge is unbalanced and the unbalanced voltage is impressed across the input of the audio oscillator. The audio power is thereby decreased until the cumulative power in the thermistor is restored again to its constant value.

At this point, the bridge is balanced and no further change occurs in the audio signal. The output of the audio oscillator, which is then a function of the RF power applied to the thermistor, is displayed on a meter suitably calibrated in watts and dbm.

CIRCLE READER SERVICE CARD 110



ELECTRONICALLY VARIABLE ATTENUATOR

This broadband coaxial attenuator, called V PAD, is electronically variable from 10 to 25 db. The variation is continuous, being a function of the solenoid current, with the maximum attenuation requiring 30 ma at S Band and 70 ma at X Band. Other models are available with attenuation as low as 3 db over the 2 — 10 kmc range. Featuring low VSWR, light in weight, small in size, having no moving parts, V PAD offers increased versatility for buffer and pad applications in signal generator, search receiver and power measuring circuits. Being electronic, this coaxial device also serves as an amplitude modulator for microwave RF.

CIRCLE READER SERVICE CARD 111

NEW TWT GIVES 100 MILLIWATTS OUTPUT AT 55,000 MC

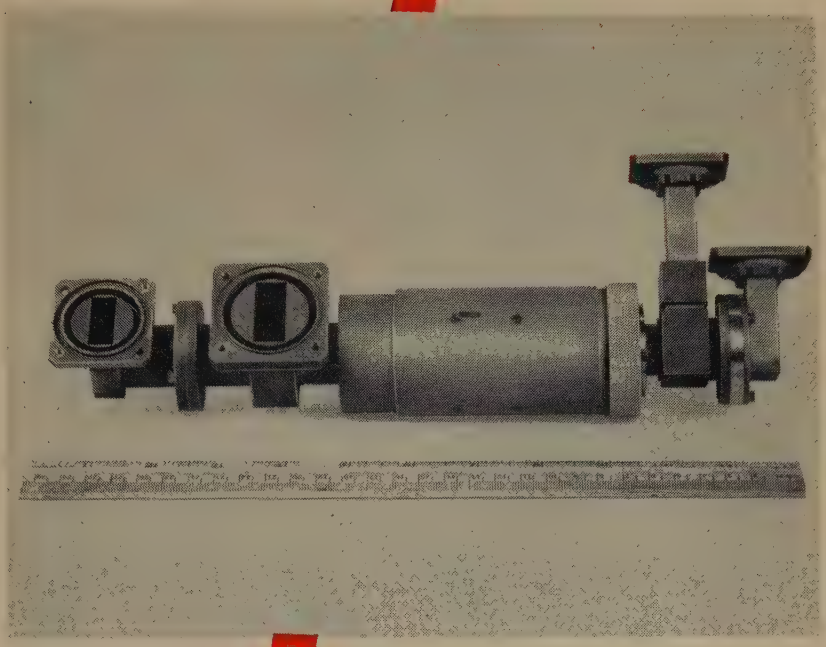
A traveling-wave tube which provides CW powers of 100 milliwatts or more at 55,000 megacycles with a bandwidth of 10,000 megacycles is in an early stage of development at Bell Telephone Laboratories. The tube was described here at the annual convention of the IRE Professional Group on Electron Devices in a paper prepared by W. E. Danielson, H. L. McDowell and E. D. Reed of Bell Laboratories.

Interest in frequencies in this range has been sparked by the possibility of long distance transmission at millimeter wavelengths using a circular electric mode in round wave guide pipe buried in the ground. The tube described is intended for use as a power amplifier in such a communication system. It has produced ten times more CW power output than has previously been reported for any other amplifier at this frequency.

In this tube a 7000 volt, 3 milliampere electron beam is projected through a 4 inch long helix having a bore of only 15 mils. This helix is made from copper-plated molybdenum wire wound at 110 turns per inch. With a magnetic focusing field of about 1500 gauss, the beam current intercepted by the helix is held to 5 per cent or less. A converging electron gun is used so that cathode current density is held to about 1 ampere per square centimeter — a value which should make a cathode lifetime of thousands of hours possible.

Although similar in principle to helix type traveling wave tubes used at lower frequencies, the millimeter wave tube required a completely new design approach because of the small sizes involved. The required degree of precision is obtained by a combination of optical alignment techniques and specially selected machining operations.

Experimental tubes have been tested at 55 kmc and have given CW output powers ranging from 125 to 200 milliwatts. Gain at maximum output is 19 db and at low level is 25 db. These results show that the basis has been laid for a practical broadband travelingwave amplifier with CW power outputs of 200 milliwatts or more at 55 kmc.



SAGE

Pictured above is a typical Sage development. The dual channel rotary joint is designed to cover the frequency range from 8600 to 9600 MC. The maximum VSWR for either channel is 1.1. Wow is negligible. The high power channel has been tested up to 250 KW peak power with no evidence of breakdown. The unit is completely pressurized and operates over a wide range of temperature.

CIRCLE READER SERVICE CARD 15

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COMPANY PROFILE

BOMAC

BOX SCORE

NAME: Bomac Laboratories, Inc.

LOCATION: Beverly, Massachusetts.

PRODUCTS: TR, ATR, Pre-TR tubes; Shutters, silicon diodes, klystrons, magnetrons, travelling-wave tubes, reference cavities, microwave components, special tubes and systems.

HIGHLIGHTS: Teamwork, the guiding principle at Bomac, has brought this firm in a little over ten years to the position of being, according to its directors, the largest independent tube manufacturer in the world.

Left to right: Richard J. Broderick, Treasurer; Harold Heins, Vice-President, Engineering; Lewis Tremblay, Vice-President, Production; Harold Booth, Executive Vice-President; Henry J. McCarthy, President.

BOMAC LABORATORIES, INC., was the first industrial firm to locate along "Route 128," the superhighway that describes a vast arc around the city of Boston. This is but a small tribute to the progressive thinking of the Company's Directors. Today, Route 128 is lined with hundreds of assorted industrial plants. BOMAC, symbolically or not, is still first, located as it is on a 35-acre plot at North Beverly, Mass., not far from where the peripheral highway meets the sea.

History

The name BOMAC is derived from the names of its co-founders, Harold C. Booth and Henry J. McCarthy. These two men joined their unusually complementary abilities to form the company in 1947.

Harold Booth has had a long association with the electronics industry, having started his career with the Raytheon Manufacturing Company in 1932. In 1939 he joined Sylvania Electric Products, Inc., and became Superintendent of the Electronics Division. During World War II, he was responsible for the development of many new techniques in the production of gas switching tubes, magnetrons, hydrogen thyratrons and semiconductors. In 1946 he became manager of the Production Development Section of the Lamp Division at Sylvania.

Henry McCarthy, with a Physics A.B. from Dartmouth and graduate work at Harvard's famed Cruft Laboratory,

Herb Alexander at the board with the microwave design engineering group discussing TR tube design problems.

joined Sylvania Electric Products, Inc. in 1933 as staff Engineer in the Radio Tube Division. During World War II he became Manager of Engineering of the newly formed Electronics Division. Mr. McCarthy holds many patents in the electronics field, and serves on the staff of MIT as Consultant.

In 1947, a happy fusion of years of production experience, as represented by Booth, and engineering talent represented by McCarthy, occurred when both men resigned from Sylvania in order to form BOMAC. The infant firm began with about 1500 square feet of rented floor space and eight employees. The initial work was of a laboratory nature, and involved the development of TR and ATR tubes. Incorporation took place in 1948 in order to facilitate the expansion which was already causing the small firm to burst at the seams. In 1951 operations were begun on the present site in the first structure of the present complex of buildings.

The Korean "police action," which brought about a hasty re-activation of all sorts of military equipment, and a vast need for Radar tubes and components, found BOMAC in an excellent position to supply many elements of these needs. It was this period that was the turning point for BOMAC. From a volume business of about $1 million in 1949, the growing firm found itself, in 1952, with an annual volume of $4 millions. Further expansion took place during these years, and today BOMAC operates in an ultra-modern plant with a general production space area of 110,000 square feet plus 20,000 square feet for storage and future expansion.

Apropos of plant and facilities, it may be appropriate to note here that BOMAC received national recognition for having the best landscaped plant in the country, a distinction in which the management takes no little pride. Location, too, has had a happy result in that nearly 95% of the employees live within eight miles of the plant. Ease of access and pleasant living surroundings are some of the reasons the company sets forth as making BOMAC attractive to its staff.

People

BOMAC is piloted by a five man Board of Directors. Henry McCarthy and Harold Booth, whose personal histories we touched upon above, are President and Executive Vice-President respectively, and exercise what was called "floating control" over the corporation.

Harold Heins, Vice-President, Engineering, is in charge of all phases of Research and Development. Mr. Heins, B.S., M.S. in Physics at MIT in 1927, has been with the firm since 1948. He was deeply involved in working on Microwave problems at the beginning of World War II, including development engineering on magnetrons, klystrons, gas switching tubes and semiconductors and is the author of numerous papers on the application of microwave tubes.

Louis Tremblay is Vice-President, Production, production engineering and industrial engineering. He has been with Bomac since its inception having come from the position of General Foreman of a large electronic tube manufacutrer. This brought to the new company a skilled glass technician and an expert in the highly important art of glass to metal sealing.

Richard J. Broderick, Treasurer, serves also as Secretary and Controller of the Corporation, and is charged with the

Optical gauging of magnetron anode by projection

administration phase of the company activity. Dick, with an A.B. in Accounting and Economics from Boston University, joined BOMAC in 1948 after a wide experience, including service with a large Boston bank, an enlistment in the armed service in 1942, and administrative work on the staff of a leading electronic tube manufacturer after service discharge.

This five-man board of Directors sits at regularly scheduled monthly meetings, and it is in these meetings that is fostered the teamwork concept that company officials say is responsible for BOMAC's rapid growth. The closely knit inter-relationship of the three main divisions of the company, Administration, Engineering and Production, each represented on the Board of Directors, results in a thorough discussion of all phases of a problem. To quote Dick Broderick, "We just don't dictate a new product; it must be thoroughly chewed over by the new products committee first . . . if a man says it's good in committee, he isn't going to fight it later on."

Harold Booth also has been quoted on the importance of teamwork in the BOMAC scheme of things. He replied to a question as to the reason for BOMAC's success in these words — "Hard work, cooperation and teamwork, plus a staff of highly skilled people."

Staff

BOMAC prides itself on having the production know-how and the people capable of forwarding new developments in the microwave field. They cite a 20% to 30% backlog in development, which furnishes a constant feed of new ideas into the production lines.

The company has a staff of 85 engineers, electrical, mechanical and electronic; approximately 50% of these are engaged in R & D.

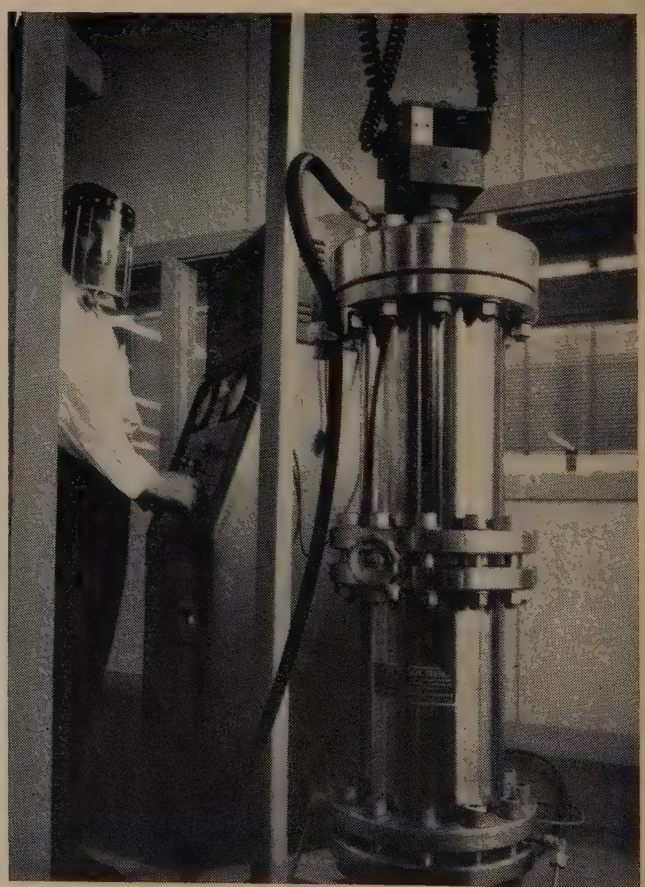
In the main body of the plant there are about 700 employees with scores of the various skills needed in the rather specialized production of the company. About sixty percent of these are women; microwave tube manufacturing is an industry where hand-assembly methods are still the only means of quality production, which accounts for the large percentage of female help. Salaries and hourly rates, plus fringe benefits are said by the company to be equal to or better than the average in the industry; and these are augmented by a profit-sharing plan approximately equal to 15% of wages. This plan has been in operation since 1952. There is now over $1 million in this profit-sharing fund, administered by the Old Colony Trust Company of Boston, and the fund continues to increase appreciably due to investment proceeds. The fund is wholly company-provided; and in this way the management feels that the teamwork concept is extended to every BOMAC employee. That this concept works is pointed up by the low employee turnover, which records show is consistently under 5% per year, and this mostly accounted for by visits of a long-legged bird.

BOMAC is also involved with the cooperative student program at Northeastern University; this has proved valuable as a source of trained help. BOMAC encourages employee self-improvement in a very practical way, in that it will pay one-half the cost of tuition and books incurred in the successful completion of an approved course of study.

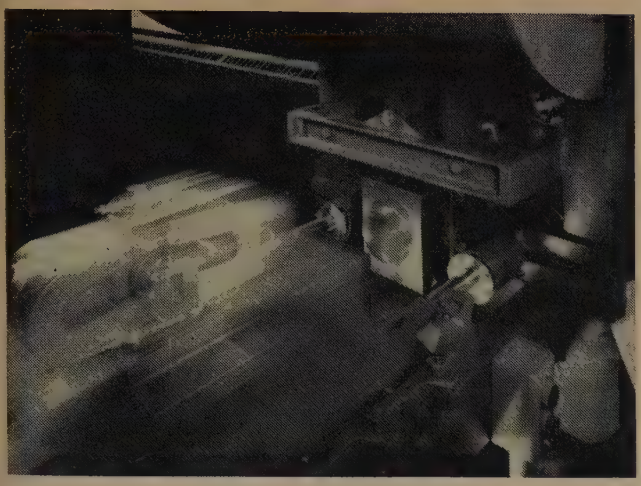
Products

Company brochures point out that "BOMAC products are used wherever radar serves." This also involves BOMAC in most missile programs.

From the handful of tubes originally manufactured, the company now makes more than 800 separate tube types.



High-G snock test on reference cavity under operating conditions



Shock test on power tube

General microwave assembly and testing area

Originally producing only passive devices, a market analysis indicated expansion into the magnetron and klystron field. Much research went into the feasibility of building a subsidiary plant in California for the production of these power tubes; and the result of the investigations, a completely independent plant, building 5, located 200 yards away from the main buildings. Building 5, then, not only manufactures power microwave tubes, but serves also as an experiment in subsidiary plant operation without the disadvantage of 3000 miles separation from the home office. In this plant are produced magnetrons for all bands, as well as special types to customers specifications, and klystrons for all applications. The main plant produces passive devices, TR, ATR, pre-TR tubes, shutters, reference cavities, silicon diodes, h-f triode oscillators, surge protectors, custom designed duplexers, noise source tubes and pressurizing windows.

With the emphasis on reliability in military specifications increasing sharply, BOMAC points out that it has the finest environmental testing setup available today. In the case of a particular small triode, a test is provided that, under operating conditions, can produce a shock of 120,000 G's. Magnetrons are subjected to shock of 20,000 G's. A hydraulic ram provides a shock of 1000 G's for 5 milliseconds.

Industry Outlook

From the foregoing, it is obvious that Bomac is prepared for any eventuality; and indeed, projections of expected increase in the entire microwave tube industry seem to warrant these measures. It has been estimated that volume sales of power tubes reached $160 million in 1958. An increase of 25% in 1959 is projected.

Other sources studying the industry foresee a steady increase in microwave power tube sales. Estimates range from the conservative 150 million to over 200 million by 1963. Both these projections indicate a healthy growth in this phase of the microwave business.

Present and Future

In a recent article on the Electronic Industry in "fortune" magazine, BOMAC was singled out as a "baby blue chip," and such attention begs several questions. Certainly BOMAC merits this attention. Its books show a volume of $8.6 million in 1957; volume will exceed $10 million in 1958. As for next year, the Directors expect an increase of from 20% to 25%. What about these insistent rumors of merger? According to Executive Vice-President Booth, there have been many inquiries, but "no negotiations are under way." Recently, talk of a merger was mentioned in a business magazine, but to date, nothing has materialized.

BOMAC has built itself to its present position without stock issue, loans, or mortgages. All of which leaves the outside observer to scan BOMAC with a speculative and admiring eye, with the knowledge that the object of his speculation and its people will be in the forefront of activity in this fascinating microwave industry.

— J. W. Hughes

Bomac Laboratories Inc. Main Building

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CIRCLE READER SERVICE CARD 24

GEN. TELEPHONE AND SYLVANIA MERGE

Boards of directors of General Telephone Corp. and Sylvania today voted approval, in principle, of the merger of Sylvania into General Telephone. The details, including the legal steps involved, are being formulated, and, when completed, will be submitted to the share owners of both companies.

In connection with the proposed merger, the General Telephone Board of Directors also voted to recommend to its share owners a change in the name of that company to "General Telephone & Electronics Corporation."

Donald C. Power, President of General Telephone, and Don G. Mitchell, Chairman and President of Sylvania, said that the plan under consideration would involve the issuance of one share of General Telephone common stock for each share of Sylvania common stock.

It is contemplated that Mr. Power will become Chairman of the Board and chief executive officer of the parent company, and that Mr. Mitchell will become President.

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CIRCLE READER SERVICE CARD 25

Microwave Impressions of Russia

By DAVID INGALLS
President

AIRTRON, INC., LINDEN, NEW JERSEY
(a division of Litton Industries)

Notes of the Industry

DAVID INGALLS, President of Airtron, Inc., a division of Litton Industries, is the originator and founder of his organization.

Graduating from Massachusetts Institute of Technology in 1934 with a degree in mechanical engineering, he joined the engineering department of Titeflex, Inc. He rapidly advanced to the position of Chief Engineer and played a major role in the growth of that company.

In 1946 he founded Airtron, Inc., to manufacture radar and other microwave electronic equipment. The organization grew rapidly and he continued to give it his personal leadership as President. In 1958 Airtron became a wholly owned division of Litton Industries and Mr. Ingalls became a Vice President of that organization, continuing as President and Chief Executive of Airtron, Inc. The company now operates from a new headquarters in Morris Plains, New Jersey, with manufacturing plants in Linden, New Jersey, and Los Angeles, California.

In addition to holding many patents and being a member of IRE, Mr. Ingalls is a member of the Board of Directors of the Union County Safety Committee and serves as a Director of the Community Bank, Linden, New Jersey, Airtron, Inc. (a division of Litton Industries) and Airtron Canada, Ltd.

"HOW GOOD ARE those Russians? How much do they know about up-to-date microwave electronics? Why are we working so hard to stay ahead of them?" Like many other Americans, I suppose, these questions have occurred to me many times over the past few years.

I wanted to see for myself. So, while visiting Airtron associated companies in England and France this summer, I took time also to spend a week in Moscow. Plans called for taking a Russian TU 104 from Copenhagen to the Russian capitol. I suppose I approached that plane with about the confidence of a person who has visualized all Russians as being eight feet tall. The pilots with their military haircuts, the hostess wearing an apron like a mother hubbard, and oxygen masks hanging on the back of the seat in front, didn't reassure me.

However, the hostess said there would be no need to put the mask on — we would be pressurized; then she served a cold dinner (which was intended to be hot) and some vodka. My wife didn't trust the liquor — so I ended my lunch with the comfortable feeling of an extra (vodka) dividend.

After a bit I wandered up forward in the plane: the cockpit door was open. I put my head in and asked, "May I come in?" In English I heard, "Come ahead." I entered the cockpit occupied by two pilots, a navigator and a "reserve" man. After a bit of friendly conversation, the man who spoke English told me that an English-speaking member of the crew was a requirement for all the planes flying to West Europe.

I asked a number of questions and he answered willingly. The radar he was using appeared in all respects like our APS 42. It was used for navigation — apparently they had no radio beacons. They did not use the radar for weather detection; apparently the pilot had never heard of such use. During the half hour I stayed in the cockpit the pilot was busy taking readings and watching his scope.

When we reached the Moscow airport we could see fourteen TU 104 planes on the field. There was also one scanning type radar which was in operation — I saw no other microwave installations. The airport and terminal looked small and old-fashioned and suitable only for one of our smaller cities.

Our Intourist guide, a well educated girl in her second year at college, spoke excellent English. When we arrived at our hotel, she met us and went right to work making plans as to what we were to do while we were there. One of the first things she suggested was a visit to the subway ("The Metro"), the Kremlin, and the agriculture and industry exhibit. She said we would also have, what she called, a free day and could do anything we wanted. I jumped at the opportunity and requested to visit one of their factories. She spent some time talking to the other guides and said that she would request permission, but it probably could not be arranged in time. The day I left I heard the permission had been quoted. If I ever make another trip I will request it in advance

The 500-acre Agriculture and Industry Exhibition on the outskirts of Moscow was very impressive. Here the Russians had many exhibits, including Sputnik, electronic test equipment, and computers. Here also were many fine machines of very high quality. We could view and examine these in as much detail as we wished. One of the other visitors remarked that he had seen no such high quality equipment in his visits to manufacturing plants.

From conversation with local people who could speak English, and others who were visiting the country, it was apparent that the people of Moscow are proud of the progress they have made. They are continually told of this progress through newspapers and bulletins, and they are conscious of living better lives than their parents did before them. From these conversations I learned that the electronic industry is directed by decisions of top level officials, and each plant is instructed to produce specified products. Once such a decision is made, money, facilities, and manhours are appropriated to assure the desired result.

I learned that Russian engineers compete with each other for assignment to the better jobs for which money has been appropriated. I got the impression that this competition among them provides considerable motivation and drive — somewhat like the competition existing within our industrial system. In addition, their engineers receive elaborate bonuses for patentable ideas and for meeting delivery dates. I understand that sometimes these bonuses equal their salaries, which are already at the top level of those paid in Russia. Engineers also have very high social standing.

I valued the comments of businessmen from Western Europe who were visiting Russia to observe production methods. One industrial manager from West Germany remarked, "The Russians have some very good production techniques. But why shouldn't their methods be good, when they produce so many items of one type? A top official decrees that a plant is to make boots, and that plant turns out large quantities of one item. If people want boots, they use that product. The result is the plants can efficiently mass produce large quantities of the same item — and this applies to almost everything that industry turns out." Also, the Russians are adept at copying western machines, and they do this whenever they need to without qualms.

I received the impression that the Russians have microwave equipment probably as good as any that we have in America. This is needed for military purposes, and the necessary money and facilities are appropriated without question. At the same time I wondered whether their production capability tended to be inflexible because it awaited the decision of some top official. I saw many television antennas on Moscow roof tops, but apparently everybody uses the same kind of television and radio sets. In the department stores all their radios had similar cases — and most were the same size. This permits effective production of the single item, but does not allow variations and the flexibility which is an important part of American industry. Russian-made cars are all similar, and they are all black and gray. Few people get to ride in those cars, however; most of them walk. The Russians know how to make fine cash registers for the stores but their engineers use the abacus for making computations. Some products have received less engineering and production attention than the more important military products that are assigned major industrial and engineering emphasis.

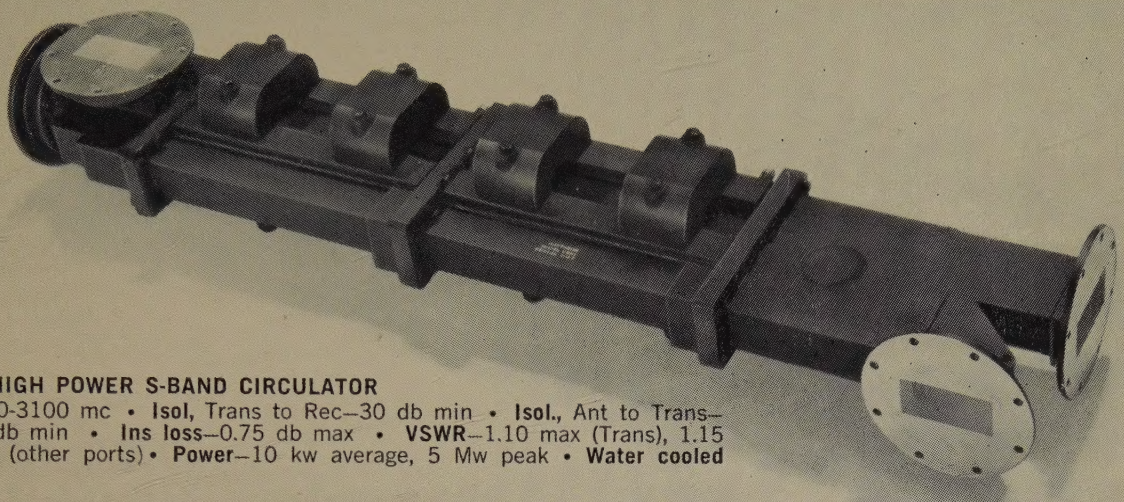
Meals also seem to come under the "less important" classification. Wherever we went for our meals we were faced with the same menu and the same lack of flavor. Even their vodka could not do much to help this problem.

After I returned to America, when friends asked my impressions of Russia, I summed my reactions up as follows:

"When I left I told everyone that I was going over to find out why I and others in the microwave industry were working so hard to build a better product." When I came home I said now that I have been to Russia and have seen what they have done, I am going to make certain that I keep on working."

Editor's note: This is the third business editorial in a continuing series for our readers. We are asking those members in the microwave business community to write on subjects that will be of interest to the industry. We invite your comments and criticisms. We hope these articles will foster discussion and that the resultant interest will provide the means of communication to and from the business and engineering groups.

Recent Raytheon developments in microwave ferrite devices



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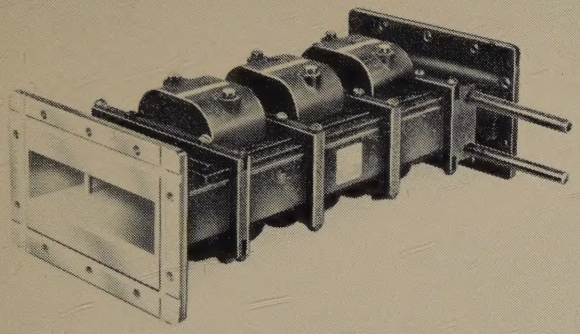
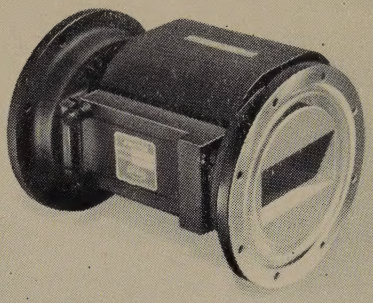
2600-3100 mc • **Isol,** Trans to Rec—30 db min • **Isol.,** Ant to Trans—20 db min • **Ins loss**—0.75 db max • **VSWR**—1.10 max (Trans), 1.15 max (other ports) • **Power**—10 kw average, 5 Mw peak • **Water cooled**



2. HIGH POWER L-BAND ISOLATOR
1250-1350 mc • **Isol.**—11 db min • **Ins loss**—0.55 db. max • **VSWR**—1.15 max • **Peak power**—3 Mw • **Av power**—2.5 kw (cooled); 1.0 kw (uncooled)



3. HIGH POWER S-BAND ISOLATOR
2750-3050 mc • **Isol**—10 db min • **Ins loss**—0.6 db max • **VSWR**—1.10 max • **Peak power**—3 Mw (pressurized) • **Av power**—3 kw (water-cooled)

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